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Commercial storage of fruits and vegetables

Canada

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Recommendations for pesticide use in this publication are intended as guidelines only. Any application of a pesticide must be in accordance with directions printed on the product label of that pesticide as prescribed under the *Pest Control Products Act*. **Always read the label**. A registered pesticide should also be recommended by provincial authorities. Because recommendations for use may vary from province to province, your provincial agricultural representative should be consulted for specific advice.

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ACKNOWLEDGMENTS

The first edition of this handbook, Agriculture Canada Publication 1260, was prepared by W.R. Phillips and J.G. Armstrong and published in 1967. The material was provided by university workers and personnel in provincial and federal departments of agriculture. The subsequent revision, Publication 1532, prepared in 1974 by Dr. S.W. Porritt (now retired), contained extensive revisions to the original manuscript and expanded the information on fruit storage.

This third edition has been revised to present recent innovations in the storage of all commodities and introduces information on controlled-atmosphere storage. Additional storage recommendations have been added for blueberries, cabbage, and carrots.

INTRODUCTION

This publication provides information for storage operators and wholesale and retail produce handlers. It contains general, biological, and engineering information, specific recommendations for storage of fruits and vegetables, and a list of references for further detailed information. The cultivars of fruits and vegetables that are produced and the growing conditions in Canada differ greatly from one area to another. Consequently, crops in each area require storage and handling procedures applicable to that area. The information provided in this publication comes from experimental work carried out in various parts of Canada and in other fruit- and vegetable-growing areas where growing conditions are similar.

A number of chemical treatments that improve the storage characteristics of some fruits and vegetables are suggested. It is important to ensure that legal regulations that may limit the use of chemicals to a particular commodity in any country or region are observed. These regulations are designed to protect the health of the consumer. They pertain to residual amounts of chemicals left in or on the product by the treatment. Before using any chemical, consult the Health Protection Branch, Health and Welfare Canada, Ottawa, Ont., or one of its regional directors or inspectors. Mention of a trademark name or proprietary product does not imply its approval to the exclusion of other products that may also be suitable.

COOLING AND STORAGE

The function of a fruit or vegetable storage is to provide an environment that will permit produce to be stored as long as possible without deterioration of quality, which is a composite of flavor, texture, moisture content, and other factors associated with edibility. A desirable environment can be obtained by controlling the temperature and composition of the atmosphere.

When fruits and vegetables are harvested, they are removed from their source of water and nutrition and soon start to deteriorate. Harvesting stimulates metabolic changes associated with ripening and senescence. Depending on temperature, there may be a greatly increased respiration rate, accelerated softening, water loss, and changes in chemical constituents such as pectins, starch, sugars, and acids. The quality and storage life of fruits and vegetables may be seriously affected within a few hours of harvest if the crop has not been precooled promptly to control deterioration. All other factors in handling and storage are of secondary importance. However, factors other than temperature also affect the storage environment. Because stored fruits and vegetables are living matter, they use oxygen and give off carbon dioxide and other volatile substances into the storage atmosphere. These gases must be kept within certain limits or damage will result. Moisture loss, if uncontrolled, may result in shriveling; and excessive moisture may contribute to the growth of microorganisms and deterioration.

FIELD HEAT AND RESPIRATION HEAT

The field heat of the produce—sometimes referred to as sensible heat—is the main heat source in a storage and puts the greatest load on the cooling system, especially during the harvest period. Field heat represents the heat that must be removed when cooling produce and containers to the desired holding temperature. With increased mechanization in harvesting and use of bulk handling, heat loads may reach unusually high levels and may sometimes exceed the cooling capacity, particularly in some of the older storages.

Heat is one of the products of metabolism in all living cells, and this metabolic heat contributes to cooling problems in storages. The amount of metabolic or respiration heat given off by stored produce varies with the kind of commodity, its age, and its temperature. Heat generated by products with a characteristically high rate of respiration may contribute substantially to the cooling load. Heat also hinders rapid cooling and, if air movement is inadequate, may lead to localized heating and rapid deterioration of the product.

PRECOOLING

Adequate cooling and temperature control cannot be achieved if the type of package and method of handling prevent rapid heat transfer from the produce to the cooling medium. Under some circumstances, special precooling procedures are warranted to maintain an adequate level of quality in the product.

The greatest refrigeration load occurs when the storage is being filled with hot produce that must be cooled to the required holding temperature. Once field heat has been removed, refrigeration requirements are greatly reduced and arise mainly from heat leakage into the storage and from heat of respiration. Cold storages must be designed so that cooling can be accomplished rapidly while uniform holding temperatures are maintained in the remainder of the produce. Alternatively, some form of precooling must be used, such as forced air, chilled water, or vacuum cooling.

One precooling method makes use of high-velocity cold air in specially designed rooms or tunnels where produce is stacked so as to provide maximum exposure to the air. This form of precooling is used for many products delivered to the market directly after harvest (60, 119).

More recent modifications of forced-air precoolers utilize humidified chilled air that is forced through product loads to precool produce with minimum weight loss resulting from desiccation. Filacell® (Pressure Cool Co., Indio, Calif.) units use evaporator coils to chill a reservoir of water (water plus eutectic to achieve temperatures of less than 0°C) that is cascaded down a vertical tower with a high-velocity countercurrent airflow blowing upward. The resulting humidified chilled air rapidly precools the produce when forced through pallet loads. The Filacell® or air-washer-type units are designed for maximum cooling loads and rely on continuous mechanical refrigeration of the water-heat exchange medium. These units are designed for continuous operation and can be used for long-term storage near 0°C.

A recent storage design, developed in England and based on the air washer principle, employs the buildup of ice in the water exchange medium during periods of off-peak electrical rates. The ice is then melted as produce is precooled during high rates of electrical usage. Basically designed as a forced-air precooler, the ice bank cooler uses approximately one-half the power of conventional mechanical refrigeration systems, as cooling momentum is provided by accumulated ice reserves. The ice bank cooler has the advantage of using off-peak electrical rates for ice generation and can draw less current during periods of maximum cooling demand, which permits reducing compressor capacity. The main disadvantage is the inability of this system to cool produce to 0°C. Under normal circumstances, minimum temperatures of 1.0–2.5°C can be obtained within 2–8 hours.

Produce with a large surface area-to-volume ratio may be optimally precooled by forcing chilled air horizontally through the product load. However, for produce with a small surface area-to-volume ratio it is recommended that chilled air be forced up (vertically) through the product stacks for maximum precooling.

Hydrocooling, in which cold water is used to transfer heat from the product, is one of the most effective methods of precooling. It is used extensively for commodities such as corn, asparagus, celery, carrots, radishes, and peaches (5, 83, 119, 185). By this process, the produce is immersed or exposed to a spray or cascade of cold water. Unsatisfactory results with hydrocooling are caused mainly by insufficient cooling time, exceeding the capacity of the refrigeration unit to keep water cold, or by failing to provide adequate exposure of the product to the water.

Contact icing is a cooling method in which shaved or crushed ice is added to the top of the product in the container or to the top of the load of produce. It is often used in rail shipments to cool the load in transit. Lettuce, spinach, radishes, carrots, and other commodities that lose moisture readily are often cooled in this way (166, 184). The application of liquid ice (consisting of 60% crushed ice in 40% water) increases the rate of produce cooling by completely surrounding the produce with ice.

Vacuum cooling is one of the most effective precooling methods for leafy vegetables with a large, open surface area. Vegetables such as lettuce, spinach, and celery are adapted to vacuum cooling, whereas cabbage and Brussels sprouts are not suited to vacuum cooling because of the tightness of the head. This procedure uses the principle of water boiling at lower temperatures as the pressure is reduced (water boils at 0°C at a vacuum of 4.6 mm of mercury, whereas at standard atmospheric pressure (760 mm) water boils at 100°C). Cooling results when water evaporates at the lower pressures and the water vapor complex absorbs heat (heat of vaporization of water at 0°C = 2500 kJ/kg). The advantage of the vacuum method is that a packed product such as lettuce can be cooled quickly and uniformly. Product temperature can be reduced by 6°C during evaporation of each 1% of surface moisture and water in the produce. Prewetting of the produce reduces water loss somewhat (9, 10).

HUMIDITY

The quality of fresh produce in storage depends to a great extent on the humidity. Humidity is more difficult to control than temperature and often does not receive adequate consideration when storages are designed. If the air is too dry, there may be enough water loss to affect the texture and cause visible shriveling or wilting. It can even make the product unsalable. Fruits such as apples and pears are most

resistant to moisture loss, but during several months of storage they may lose 2–3% or more in weight because of water loss. A moisture loss of 4–5% results in spongy texture and visible shriveling of apples and pears. Excessive humidity, on the other hand, is conducive to growth of mold and decay organisms, particularly when water droplets form on the surface of pome and drupe fruits. There is increasing evidence that very high humidity, particularly in the early part of cold storage, can contribute to physiological disorders in certain cultivars of apple. With most commodities, however, the problem is one of maintaining sufficient moisture in the storage, although a few vegetables such as onions, garlic, squash, and pumpkin require low relative humidity.

Vegetables are, in general, very susceptible to moisture loss in storage, with leafy vegetables losing moisture most readily; in an unfavorable environment they can suffer damaging water loss in a few hours. A moisture loss of 4% or more may necessitate trimming of the outside wilted leaves (200). Softening or wilting of root crops or cabbage heads is be apparent when the total moisture loss exceeds 5–6%, whereas moisture loss in excess of 8% renders the product unsalable. Unlike pome and drupe fruit, which is susceptible to increased decay and physiological disorders at high relative humidity, most vegetables requiring storage at high relative humidity are resistant to increased decay or physiological disorders. For most vegetables that are susceptible to rapid water loss, the incidence of decay is usually not accelerated by the presence of condensation on the surface of the product if storage temperatures are maintained near those recommended for the product.

For a given relative humidity, moisture loss is greater with high produce temperature. Thus, to minimize moisture loss it is essential to cool the produce promptly after harvesting.

In a refrigerated storage, the best way to maintain high humidity is to use an evaporator coil that is large enough to provide rapid cooling of the air without requiring operation at a low temperature. An undersized cooling coil must be operated with a low surface temperature to cope with demands, especially during loading of the storage, that cause moisture to condense and freeze on the coil and effectively remove water from the storage environment. This lowers the humidity and results in abnormal moisture loss from produce. Also, the accumulation of frost reduces the air flow over the coil and lowers its cooling efficiency still further. Figure 1 shows how humidity of the storage atmosphere is related to the temperature of air leaving the coil. The use of jacketed storages is one way of providing for a large cooling surface to minimize product moisture loss. However, the main constraints in the application of jacketed storages to fresh produce are lack of precooling capacity, growth of microorganisms, changes in product flavor and texture in response to high humidity, and

additional construction costs (93, 94, 147). Where adequate humidity can be obtained in no other way, water should be added to the storage by humidifiers that introduce water as a fine spray or as steam, or by sprinkling the floor. It is extremely important not to spray water directly on the produce because any water on the surface of the produce encourages microbial growth. Alternatively, produce stored in bulk bins (about 385 kg) or field boxes (about 20 kg) may be enclosed with 38 µm perforated polyethylene (or equivalent) to maintain an atmospheric humidity of 94–98%. *Caution*: A polyethylene barrier around produce that has not been precooled slows field heat removal and increases deterioration of the product.

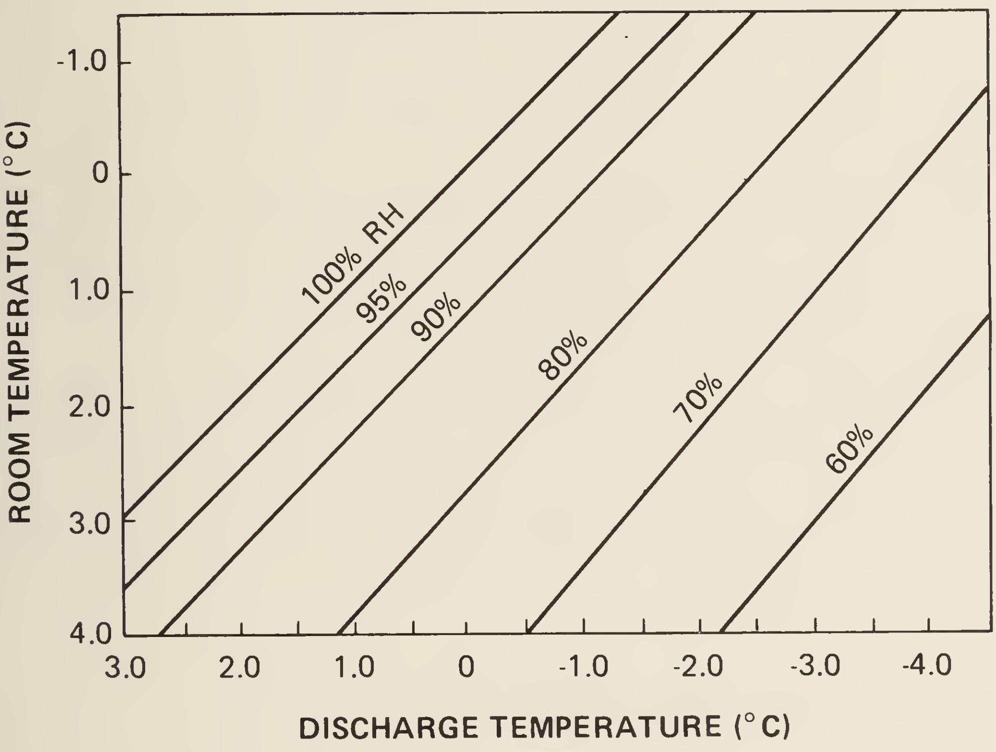

Figure 1. Relationship of relative humidity of room air to temperature of discharge air from the evaporator coils. To obtain a temperature of 0°C and 90% RH in a room, the minimum temperature to which air may be cooled without removing moisture by condensation is found on a vertical line through the intersection of the 90% RH line and 0°C room temperature line, about –1.4°C. (This graph was developed from values in Table 11, Determination of Thermodynamic Properties of Moist Air in ASHRAE Guide and Data Book 1961.)

In this publication, humidity is expressed in terms of relative humidity (RH). RH is the actual amount (or percentage) of moisture in the atmosphere at a given time as related to the maximum amount (100%) that could be retained at the same temperature. The movement of moisture between an object and the atmosphere depends on the relative, not the absolute, humidity. The RH of the atmosphere changes with the temperature. As the temperature is reduced, the RH increases to 100%, at which level the atmosphere is said to be saturated. The temperature at which this occurs is called the dew point.

SWEATING

Cold produce exposed to a warm atmosphere usually becomes moist or even wet, which is referred to as sweating and is caused when the warm air loses moisture as it is cooled on contact with the produce. Figure 2 shows how the occurrence of condensation at a given temperature is related to the humidity and temperature of the atmosphere.

One way to avoid sweating when produce is removed from storage is to warm it gradually to a temperature at or above the dew point of the atmosphere to which it will be transferred. When condensation cannot be avoided, produce subject to decay should be marketed promptly after removal from cold storage.

Sweating may also occur in storages where relative humidity is maintained near saturation (98–100% RH). This phenomenon will result from fluctuations in storage air temperature, which occur after a defrost cycle. Evaporator coil temperature should be reduced at least to product temperature before the circulation fans are engaged, which prevents surface water from forming on the produce and retards fungal infections.

FREEZING AND CHILLING INJURY

Injury from chilling should not be confused with that caused by freezing. Freezing damage is always associated with temperatures below the freezing point of the produce, usually about –3 to –1°C (204). Severe freezing results in general softening and discoloring of the tissue, and the damage is readily apparent. Depending on the duration, moderate freezing may result in localized tissue injury, notably browning of the vascular elements, or it may not cause any apparent damage but results in more rapid deterioration of the product. Some fruits and vegetables such as apples, pears, carrots, parsnips, and cabbage are not immediately injured by moderate freezing, but others such as potatoes, celery, and cauliflower are

damaged by any ice formation in the tissue. When tissue is frozen, it usually has a glossy appearance, which in moderate freezing might be quite localized. When freezing is fairly extensive, apples and pears may be wrinkled and shrunken, sometimes by as much as 10% in volume. Frozen produce should be thawed promptly, and if it must be moved it should be handled very carefully to avoid jarring, which can increase injury. Compression of frozen produce, such as pressure applied by the fingertips, results in distinct areas of injury after the fruit has thawed.

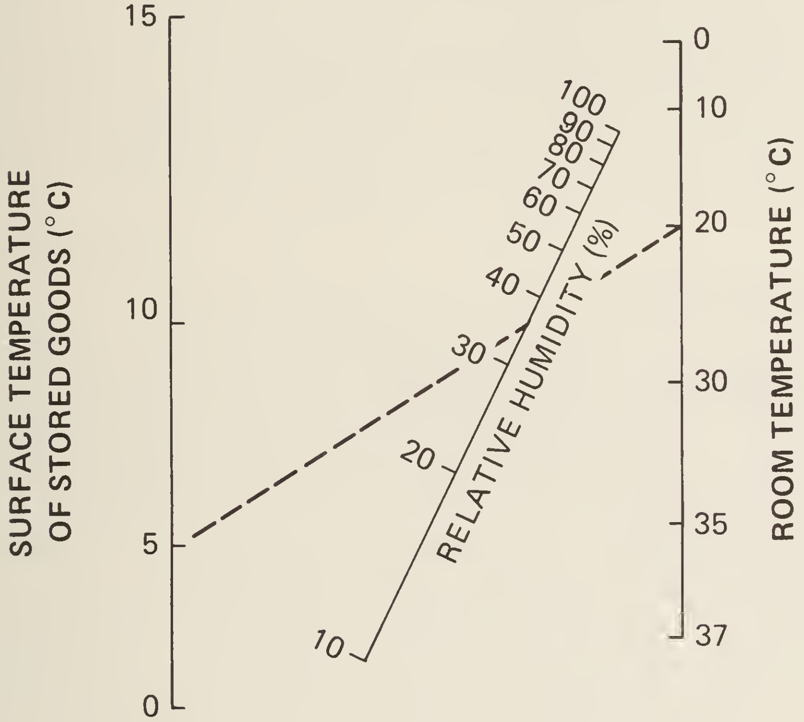

Figure 2. Relationship of room temperature, relative humidity, and surface temperature of the object to occurrence of condensation or sweating. In the illustration, room temperature is 20°C and relative humidity is 37%. An extension of a line through these points intersects the surface temperature scale at 5°C. Produce at this temperature or lower would be subject to sweating. (This material was provided by C.A. Eaves, Research Station, Kentville, N.S.)

Plant material can be cooled to temperatures below the freezing point (supercooled), sometimes by as much as 5 to 6°C, for a brief time without ice formation or observable damage. Pears have been kept at 0.5°C below their freezing point for as long as 6 weeks without freezing and damage (114). Jarring or vibration of supercooled material causes immediate ice formation, hence freezing in transit often results in unusual and extensive injury to the product.

Chilling injury is caused by a metabolic disturbance of the tissue at certain temperatures above freezing. This injury may result from brief exposure during storage or transit, or before harvest, to temperatures below a critical level of the specific commodity. The degree of injury depends on length of exposure and temperature. This type of injury causes pitting, discoloration, decay, breakdown, or undesirable chemical changes; these symptoms may occur in storage or shortly after removal to warmer conditions. The critical temperature, below which injury may be produced in fruits and vegetables (such as eggplant, green beans, cucumbers, squash, and tomatoes) subject to chilling, is usually about 7–13°C (61, 119, 137, 164, 167).

CHEMICAL INJURY

Produce in storage may be damaged from contact with chemicals, especially those that are more volatile. Ammonia refrigerant leaking into a storage room damages the skin of fruits and vegetables, particularly near the lenticels (pores) or other openings. Exposure for only 1 hour to ammonia in concentrations as low as 0.8% has caused severe injury to apples, pears, bananas, peaches, and onions. With longer periods of exposure, ammonia concentrations, so low as to be barely detectable by odor, cause damage (106, 159). Ammonia injury, apparent as dark pigment discoloration at the lenticels of apples and pears, does not cause permanent damage if the length of exposure and the concentration are not too great and if the storage is thoroughly aerated when trouble is detected. Small leaks of fluorocarbon refrigerant do not normally cause damage, but several recent reports indicate that apples have been damaged (regular, sunken areas on fruit surface) by massive fluorocarbon leaks.

WAXES

Waxes are applied to fresh fruits and vegetables to enhance their appearance and prevent moisture loss (66, 69, 149). Wax is usually applied after the produce is removed from storage and while it is being prepared and packed for market. Waxed apples and pears, however, are often returned to the storage after waxing and packing. Turnips and sometimes parsnips are usually waxed by immersion in hot

paraffin wax containing 1% paraffin oil at 120–135°C (53). When other vegetables, such as carrots, beets, cucumbers, and tomatoes are waxed, the material is applied as a cold emulsion by means of a brush or a spray. Most of the apples and pears packed in Canada and the United States today are waxed by cold emulsions containing carnauba wax, paraffin, and sometimes shellac (172).

The waxing of apples and pears helps to control moisture loss and improves appearance, particularly of red apples. Internal levels of carbon dioxide and ethylene are higher in waxed apples, but there appears to be little consistent effect on acidity, firmness, soluble solids, or physiological disorders (116). The quality of sweet cherries can also be maintained by applications of shellac-based emulsions or polysaccharide–protein–oil emulsions (95). Wax coatings applied to sweet cherries inhibit water loss, stem shriveling, discoloration, and the development of surface pitting in response to mechanical damage. Cherry waxing also extends fruit shelf life by enhancing fruit brightness and gloss.

PLASTIC FILMS

Transparent plastic films of various kinds are used extensively in packing produce for retail sale. The commodity may then be stored for only a limited period; the film package usually has adequate provision for gas and moisture vapor transmission (190, 191).

Where plastic films, usually 38 µm polyethylene, are used as box liners for packed fruit during cold storage, more attention must be given to the gas exchange characteristics (67). Initially, plastic liners were tried as a modified-atmosphere (MA) storage within the container. Inconsistent and sometimes adverse levels of carbon dioxide have limited this type of use mainly to sweet cherries, which are tolerant of high carbon dioxide and low oxygen levels. Eaves (38) devised a procedure using packaged lime inserts to control carbon dioxide in sealed box liners, but the technique is not used extensively. It has become common practice, however, to pack Golden Delicious apples and Bartlett and Anjou pears in perforated polyethylene liners, mainly to control moisture loss.

It is imperative that sealed liners, such as those used on cherries, be slit open when the produce is taken out of cold storage. Because pears have a high respiration rate when ripening, it is also good practice to slit open the perforated box liners when pears are removed from cold storage. Polyethylene liners with fine, multiple perforations that give suitable control of gas and moisture vapor trans-mission in cold storage are not suitable for controlled atmosphere (CA) storage. Where liners are used on packed fruit in CA storage, additional perforations are needed, particularly for pears, to prevent carbon dioxide from exceeding a critical level, which may be less than 2%.

SANITATION IN STORAGE ROOMS

Rot and mold organisms are sometimes troublesome in storage rooms. They cause objectionable odors that may taint stored produce, and they cause deterioration of containers and wooden structural materials. It is difficult to eradicate these organisms, but sanitation measures can be applied to minimize their adverse effects. Any accumulation of damaged or decayed produce in partly filled boxes should be removed from the storage promptly. The most effective measure is thorough cleaning of the storage room as soon as it is empty, well in advance of the next loading date. This cleaning can be done by using a detergent such as 1% trisodium phosphate, followed by a spray of sodium or calcium hypochlorite solution, containing 0.8% available chlorine (49). After the room is cleaned, added protection can be obtained by using fungicidal paint (81). The fungicidal ingredient remains active for some time after application. A common practice in potato storage rooms is to spray the inside surface with a quaternary ammonium compound. When washing or spraying the interior with any spray material, all electrical equipment should be protected; this applies also to metal structures if corrosive materials are used. Keeping storage rooms well ventilated and at high temperature when not in use also helps to restrict growth of molds.

Neither ozone nor ultraviolet light is effective in limiting growth of decay organisms or in improving storage conditions. Ozone, even in low concentrations, is injurious to human beings and can cause damage to some commodities in concentrations as low as 0.5 ppm.

The use of activated carbon air filters to prevent odor contamination may have value in mixed storage rooms that include fruit, vegetables, eggs, and dairy products.

COMMODITY COMPATIBILITY

Although certain commodities have similar temperature and humidity requirements, it is not always desirable to store them together in the same room. Limitations are most commonly encountered because certain crops produce volatile substances that affect other commodities. Apples, pears, peaches, plums, apricots, and tomatoes give off ethylene gas, which even in low concentrations can initiate sprouting of potatoes, carrots, and onions; cause blanching, yellowing, or necrosis of leafy vegetables such as cabbage, lettuce, celery, and Brussels sprouts; and induce bitterness in carrots. These groups of products therefore cannot be stored in the same room or even in the same building, unless special provisions are made for ventilation. Potatoes sometimes impart an earthy flavor to fruit, particularly at high temperatures. Generally, dairy products cannot be stored with any fruit or vegetable.

CONTROLLED-ATMOSPHERE (CA) STORAGE

CA storage is the name given to the technique in which the gaseous composition of the storage atmosphere and the temperature are regulated or controlled. Air consists of about 78% nitrogen (N), 21% oxygen (O_2), 0.03% carbon dioxide (CO_2), and traces of several other gases that have no physiological significance. In CA storage, O_2 may be reduced to as little as 1% and CO_2 increased to 2.5% or more, depending on the specific requirements of the commodity stored. Levels of O_2 higher than 5% have little value in delaying senescence – 2% O_2 seems to be a fairly universal minimum level for conventional CA. Where good control can be maintained, 2.5% O_2 is an acceptable working level. However, low levels of O_2 (1.0–1.5%) further increase the retention of product quality in storage, but these levels should be applied, with caution, only to storages capable of controlling O_2 levels to within ±0.1%. An automated O_2 sampler and regulator is recommended for low O_2 applications. The increased CO_2 content in a storage atmosphere is a major factor contributing to the beneficial effects of CA storage where O_2 levels are above 2%. Tolerance for CO_2, however, may be critical for some commodities and may vary with growing conditions, the O_2 content of the storage atmosphere, and other factors. The concentration of CO_2 listed in Table 1 is sometimes less than optimal, but usually it can be used with little risk of injury to the commodity.

APPLICATION OF CA

The most important application of CA is for apple storage, but the storage life of certain other fruits (pears, sweet cherries) and vegetables (cabbage) can also be extended by this method. The advantages of CA over cold storage usually become more apparent as the storage period is extended. Not all apple cultivars benefit equally from CA storage. Most physiological disorders, however, such as scald, core browning, Jonathan spot, and senescent breakdown, as well as decay, are reduced by CA storage. Jonathan spot, for example, can be inhibited by as little as 0.5% CO_2 (36). CA storage is effective in maintaining the acid content of all apple cultivars, an important consideration in long storage of cultivars with a low acid level (127, 155). But the value of CA for some cultivars has been disappointing. For example, cultivar flavor may be partly lost or modified by long storage in CA (99), and the softening rate of some apple cultivars has not been reduced as much as expected. This applies particularly to cultivars such as Winesap, Delicious, and Golden Delicious, which can be stored successfully at low temperatures of about –0.5°C.

Several recent research developments have improved the CA storage potential and after-storage quality of apples. The refined techniques available to CA storage operators who want to improve fruit quality retention in storage and extend the marketing season include the following: low O_2 storage (1.0–1.5%), low ethylene CA storage, rapid oxygen pulldown (or rapid CA), MA storage using edible fruit coatings, and programmed CA storage.

Table 1. CA storage requirements for some cultivars of apples and pears

Cultivar	Carbon dioxide (%)	Oxygen (%)	Temperature (°C)
McIntosh*	5.0†	2.5	2.0 to 3.5†
Delicious*	1.5–2.0	2.5	–0.5 to 0.0
Empire	0.5–1.0	2.5	1.0 to 1.5
Golden Delicious*	2.0–3.0	2.5	0.5 to 0.0
Idared	0.5–1.0	2.5	0.0
Rome Beauty	2.0–3.0	2.5	0.0
Northern Spy	2.0	2.5	0.0
Stayman Winesap	5.0	2.5	–0.5
Spartan*	2.0	2.5	–0.5 to 0.0
Newtown	3.0	2.5	2.0
Jonathan	3.0–5.0	2.5	0.0
Baldwin	2.0–3.0	2.5	0.0
Macoun	5.0	2.5	3.5
Bartlett	1.5–2.0	2.5	–1.0 to 0
Bosc*	0.5–1.0	2.5	–1.0 to 0
Anjou*	1.5–2.0	2.5	–1.0 to 0
Clapps Favorite	0.0–1.0	2.0	0.0

*Improved fruit quality retention may be achieved by storing these cultivars in 0–2% CO_2 + 1.0–1.5% O_2 at the suggested temperatures. However these recommendations are tentative and should not be attempted without preliminary testing.

†2% CO_2 for first month suggested in British Columbia; 1.5–2.5°C has provided better results in British Columbia.

LOW-OXYGEN CA

Low O_2 storage uses existing airtight (20-min test, Fig. 3) CA rooms, CO_2 scrubbers, and O_2 controls. The technique is simple in that it reduces the storage O_2 level from the conventional 2–3% to

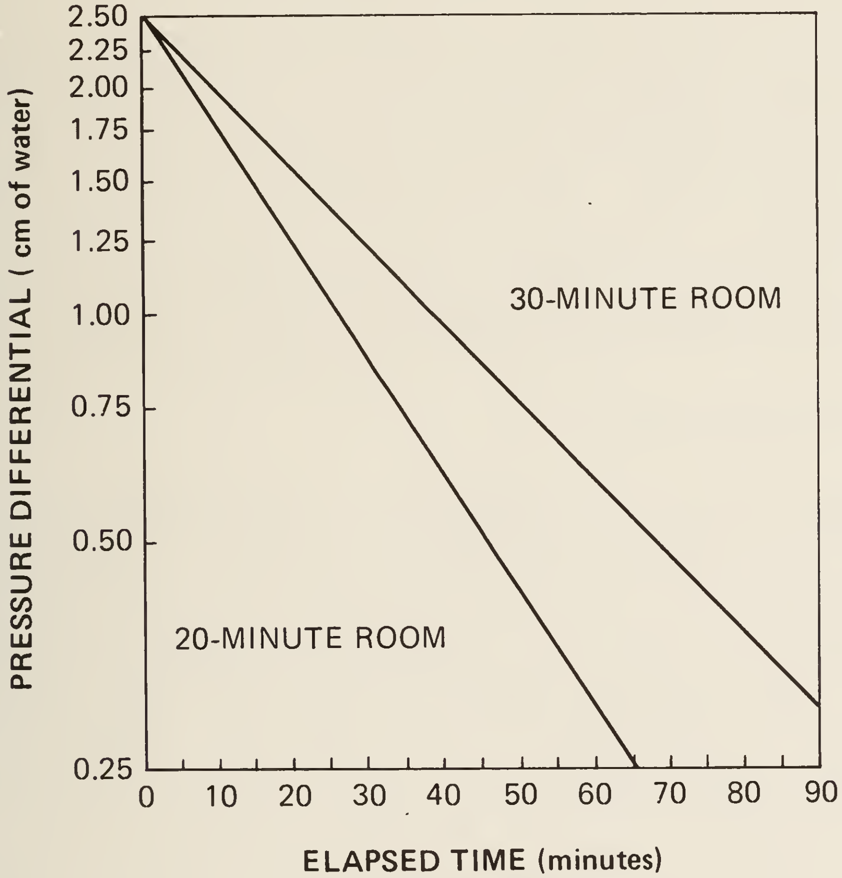

Figure 3. Leak test chart used to determine airtightness of CA storage room (11).

1.0–1.5%. In physiological terms, a level of 1.0% O_2 is below the threshold value required for fruit softening to proceed rapidly and has the potential to retain fruit texture and titratable acids of McIntosh, Cortland, Golden Delicious, Spartan, and Red Delicious cultivars (88, 96, 100, 126). McIntosh appears to be the most susceptible to low O_2 injury, which can be eliminated or minimized by selection of preclimacteric fruit lots high in calcium (Ca) and phosphorus (P). Low O_2

storage has been used commercially since 1981 in southern Ontario, where it has increased earnings each year. The main advantages to the commercial use of this technique are improved fruit firmness and titratable acid retention, an average 5–10% reduction of bruising on traditionally soft apples (McIntosh and Golden Delicious) during the sorting and packing operation, and the ability of packers with sufficient volume to provide a continuing supply to markets year round. The disadvantages of low O_2 storage include the risk of low O_2 injury resulting in product loss, the short amount of time during which the fruit is mature and must be harvested, the requirement for immature preclimacteric fruit that detracts from product quality, and the loss of characteristic flavor with extended storage. In conclusion, low O_2 storage is profitable, provided the risk of injury does not exceed 10% of the total product stored. A storage operator attempting low O_2 storage for the first time should consult local authorities for advice pertaining to his region. Small prototype trials instead of large-scale trials should be conducted over several years to allow the operator to assess the inherent risk of low O_2 injury. The use of an automated O_2 sampler and controller to maintain the desired storage atmosphere to within a range of $\pm 0.1\%$ is desirable.

LOW-ETHYLENE CA

Ethylene (C_2H_4) is an autocatalytic ripening hormone that is generated and released by the fruit. Low C_2H_4 CA for McIntosh apples uses conventional atmosphere (5.0% CO_2 + 2.5–3.0% O_2, 3°C), but requires the selection of preclimacteric fruit that is cooled immediately; O_2 pulldown by nitrogen (N_2) flushing started within 3–5 days of fruit harvest. McIntosh apples must have a midsummer application of 1000 ppm daminozide and must be harvested in a preclimacteric state (starch index 2–4) (52, 150, 177), cooled, and sealed within 5 days of harvest; atmospheric C_2H_4 level must be maintained below 1 ppm to preserve fruit firmness and retain titratable acids (107). Following this procedure, benefits in McIntosh texture may range from 4 to 18 Newtons (N) [1–4 pound-force (lb-f)] with an average firmness benefit of 4 to 11 N (1 to 2.5 lb-f). This storage treatment will return a profit to the packer if an economical commercial C_2H_4 scrubber can be developed. Several promising scrubbers are now being tested at various research centres.

The retention of McIntosh fruit quality in low C_2H_4 storage has been achieved in small experimental or semicommercial CA storages. However, C_2H_4 removal from commercial 200- or 400-t rooms is made difficult because of a large volume of headspace air, a large source of potential C_2H_4 production (fruit), and the requirement for maintaining an average of 1 ppm C_2H_4 or less in the storage air. These physical constraints require the development of an efficient C_2H_4 scrubber.

There are two methods for removing C_2H_4: chemical removal by oxidizing C_2H_4 with the use of potassium permanganate on an inert carrier and catalytic combustion of C_2H_4 on a catalyst at high temperatures (200–680°C). Removal of C_2H_4 by catalytic combustion is possible, and methods are being investigated for reducing the heat load that this technique places on the refrigeration system. Recommendations should be forthcoming for future crop years.

RAPID OXYGEN PULLDOWN OR RAPID CA

Rapid oxygen pulldown or rapid CA requires the shortest possible time for fruit harvest, room loading, product cooling, room closure, and O_2 reduction to 3%. In recent work on Golden Delicious apples, rapid CA procedures of 1–7 days were compared with establishment of CA regimens by fruit respiration, which usually requires about 21 days from room closure (88, 89, 90). This work has shown higher retention of fruit firmness 4–11 N (1–2.5 lb-f) and 2–3% higher titratable acids in Golden Delicious resulting from rapid establishment of 2–3% O_2 by either N_2 flushing or catalytic burning. Data with McIntosh apples indicate that 10 days at 0°C (3°C during O_2 pulldown) from the initial fruit harvest until the room O_2 is reduced to 3%, compared with a 1-day delay, does not consistently improve texture and titratable acid retention and is often dependent upon fruit lot and crop year (181, unpublished results). However, delays in O_2 reduction of over 10 days from initial fruit harvest result in softer McIntosh with lower titratable acids and reduce both fruit quality and storage life. It must be stressed that the 10-day maximum interval from the initial harvest until the room O_2 is reduced to 3% includes fruit harvest, room loading, product cooling to 5°C or lower, and door closure. Therefore, it is good CA practice to cool all fruit immediately after harvest, load and seal the room as soon as possible, and reduce room O_2 levels by either N_2 flushing or catalytic combustion.

MODIFIED ATMOSPHERE (MA) STORAGE

In MA storage the composition of the atmosphere surrounding the produce is generated by respiration in equilibrium with the ambient storage atmosphere as regulated by the relative permeability of a surrounding film or coating. MA can be used for produce contained in a cold storage or for produce shipped in containers enclosed in plastic film (see section on plastic film); it can also be used on individual fruit by the application of a semipermeable coating.

The apple industry in several regions of Canada has numerous small independent storage operators with insufficient volume or capital to construct their own CA storage. However, an edible fruit

coating that imposes MA on individual fruit in cold storage is currently being developed. This coating can be applied by dipping or spraying and acts as a barrier on the surface of the fruit to reduce movement of oxygen into the fruit and carbon dioxide out of it. By selection of the appropriate coating for the product to be stored it is possible to simulate various CA conditions. However, because the final atmospheric effect is dependent on the respiration rate of individual fruit and on epidermal permeability, there is much greater variation in the effective MA established than in conventional CA. Research is currently under way to estimate fruit variability in response to coating application and to determine its effect on limiting commercial application. Applications of semipermeable coating to apples and pears under laboratory conditions do, however, show significant and consistent retention of fruit firmness and titratable acids in cold storage.

PROGRAMMED CA STORAGE

McIntosh, Spartan, and Golden Delicious are resistant to low oxygen injury early in the storage season and can tolerate 1.0% O_2 or lower for a considerable length of time. However, a particular lot may sustain low O_2 injury if exposed over the entire storage season. In addition, exposure of apples to 1.0% O_2 for 40 days or more has been shown to induce changes in the fruit that retard softening even after the fruit has been removed from the low O_2 environment (Fig. 4). Programmed CA storage takes advantage of the above observations and uses two or more distinct atmosphere regimens over the storage season. Preliminary data indicate that initial exposure of McIntosh apples to 1.5% CO_2 + 1.0% O_2 for 2.5 months and subsequent storage in 5% CO_2 + 2.5–3% O_2 for an additional 5 months result in fruit quality similar to that of apples stored in 1.5% CO_2 + 1.0% O_2 for an entire 7.5-month storage period. With this technique, short-term exposure can produce a fruit texture that is similar to that achieved when the fruit is held full term in low O_2. In addition, it has the advantages of reducing the risk of low O_2 injury and the loss of the characteristic flavor of volatile substances normally associated with low O_2 storage.

Current research is providing a range of choices to improve the quality of the final product and to extend the marketing season of apples. However, each option requires improved storage management and in some cases additional capital investment. There is no question that each of the techniques discussed herein can result in a better product and increase grower returns, but the choice of using any of these procedures depends on product price, market competition, and the capability of the individual storage operator.

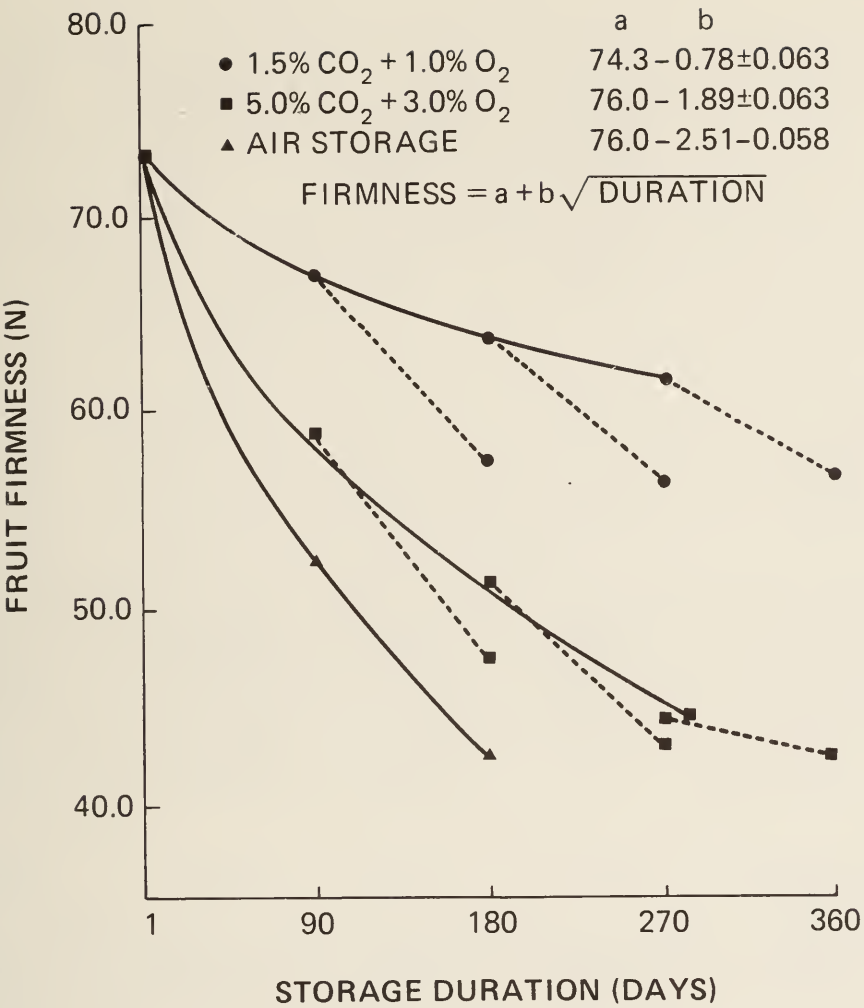

Figure 4. Firmness loss in McIntosh apples stored initially in controlled atmospheres and air and subsequent firmness loss with additional air storage (Data from Lidster et al., 1984, Can. Inst. Food Sci. Technol. J. 17:086–091).

STORAGE REQUIREMENTS FOR FRUITS

Recommendations for storing most Canadian-grown fruits are given in Table 2 and on the following pages.

Table 2. Recommended storage temperature, relative humidity, storage life expectancy, and the highest freezing point of fresh fruit

Fruit	Temperature (°C)	Relative humidity (%)	Approximate length of storage period	Highest freezing point* (°C)
Apples	–0.5†	85–96	as per cultivar and method of storage	–1.7
Apricots	0.0	85–95	1–2 weeks	–1.1
Blackberries	0.0	85–95	a few days	–0.8
Blueberries	0.0	85–95	2–4 weeks	–0.8
Cherries				
sweet	0.0	85–95	3–4 weeks	–1.8
sour	0.0	85–95	few days	–1.7
Cranberries	2.0–4.5	80–90	2 months	–0.8
Grapes, American	0.0	85–95	1 month	–1.3
Melons				
cantaloupe or muskmelon	0.0–7.0	85–90	2 weeks	–0.8
honeydew	7.0–10.0	85–90	2–3 weeks	–1.1
watermelon	2.0–4.5	85–90	2–3 weeks	–0.4
Peaches	0.0	85–95	2 weeks	–0.9
Pears				
Bartlett	–1.0	85–95	2–3 months	–1.6
fall and winter	–1.0	85–95	3–5 months	–1.7
Plums (including prunes)	0.0	85–95	prunes, 4–6 weeks plums, see text	–1.3
Raspberries	0.0	85–95	a few days	–1.1
Strawberries	0.0	85–95	5–10 days	–0.8

* Some figures are from reference 206; maximum freezing points are given to indicate low-temperature safety limits.
† See also Table 1.

APPLES

Temperature: –0.5 to 0°C for most cultivars
Relative humidity: 85–96%

The capacity of cold-storage facilities for apples exceeds that of any other fruit or vegetable, and extensive information is available on storage construction and on the handling and storage of apples (11, 49, 73, 112, 141, 144, 182, 183). Table 3 shows average or normal storage characteristics of common cultivars, but storage life, quality, and susceptibility to disease and physiological disorders can be modified greatly by weather, soil, and cultural conditions. The storage operator needs to know how the cultivar behaves locally and what to expect of various lots grown under various cultural and soil conditions. With a knowledge of the storage potential, the operator can assign incoming lots to CA or conventional cold storage or, if necessary, keep them accessible for ready observation and early sale. From time to time, small samples should be taken from various lots and allowed to ripen to check fruit condition.

The pressure test to determine flesh firmness is a good objective measure of fruit condition (62). Various types of apples have fairly characteristic flesh firmness at harvest and soften in cold storage at a predictable rate characteristic of the cultivar. Accelerated ripening caused by advanced maturity, delays in storage, or unsatisfactory cooling, is revealed by the pressure test.

Maturity

Fruit quality and storage behavior are influenced greatly by maturity of fruit at harvest. Immature fruit lacks characteristic flavor and texture and is subject to shriveling, scald, core browning, and bitter pit. As fruit becomes overmature, it is more subject to mealiness, fungal diseases, and breakdown caused by water core or senescence (39, 40).

There is no easy way to make an exact assessment of maturity, but a number of guides or indexes used by experienced people can provide a satisfactory estimate of harvest maturity. Knowledgeable people fail to harvest fruit at the correct maturity because of other reasons—adverse weather conditions, a labor shortage, or a decision to wait for better color—not because they are unable to assess maturity.

Indexes of maturity include skin color, flesh color, seed color, starch content, internal ethylene levels, ease of picking, occurrence of water core, and time from bloom (23, 25, 87, 97, 145, 150). The pressure test is a good measure of maturity for pears, but not for apples (Table 4). Storage tests and experience over several years are needed to show which of these indexes are most reliable for the cultivar and growing conditions.

Table 3. Normal and maximum cold-storage periods for some common apple cultivars and their susceptibility to storage disorders

Cultivar	Storage period (months) normal	Storage period (months) maximum	Tendency to storage scald	Other disorders likely to occur in storage
Gravenstein	0–1	3	slight	bitter pit, Jonathan spot
Wealthy	0–1	3	slight	soft scald, Jonathan spot
Grimes Golden	2–3	4	severe	soggy breakdown, bitter pit, shriveling
Jonathan	2–3	4	slight	Jonathan spot, water core, soft scald, breakdown
McIntosh	2–4	4–5	slight	brown core, breakdown
Empire	3–4	5	medium	breakdown, chilling injury
Cortland	3–4	5	medium	breakdown
Spartan	4	5	very slight	breakdown
Rhode Island Greening	3–4	6	severe	bitter pit, internal breakdown
Delicious	3–4	6	slight to medium	bitter pit, water core, internal breakdown
Stayman	4–5	5	severe	water core
York Imperial	4–5	5–6	severe	bitter pit
Idared	4–5	6	medium	breakdown
Northern Spy	4–5	6	slight	bitter pit
Rome Beauty	4–5	6–7	slight	bitter pit, brown core, soft scald, internal breakdown, Jonathan spot
Newtown	5–6	8	slight	bitter pit, internal browning
Winesap	5–7	8	medium	water core

Table 4. Recommended pressure-test readings for harvest and approximate storage life of some cultivars of pears

Cultivar	Pressure test range [Newtons (pounds-force) with 8-mm plunger]	Storage life at −1.0°C (months)
Anjou	70–50 (15.0–12.0)	4–6
Bartlett	85–75 (19.0–17.0)	2–3
Beurre Bosc	60–55 (14.0–12.0)	3–3.5
Clapp's Favorite	70–60 (16.0–13.5)	2–3
Clarigeau	60–50 (14.0–11.0)	4–5
Comice	60–40 (13.0– 9.0)	2–3
Doyenne Boussock	65–55 (14.0–12.0)	2
Flemish Beauty	60–50 (13.0–11.0)	2
Hardy	50–40 (11.5– 9.0)	2–3
Kieffer	70–55 (16.0–12.0)	2–3
Red Bartlett	85–75 (19.0–17.0)	3–4
Winter Nelis	65–55 (14.0–12.0)	4–5

Storage conditions

The need to move harvested fruit into cold storage quickly and cool it properly cannot be overstated. Picking apples accentuates respiration and ripening, particularly during warm weather. Delay in cooling after harvest can result in reduced storage life because of accelerated softening and ripening, and increased chances of scald, breakdown, and decay. McIntosh apples have been shown to soften as much as 20 times faster at 21°C than at 0°C. During lengthy storage, small differences in temperature can have obvious practical effects on condition. Most apple cultivars benefit from storage at temperatures just above the freezing point of the fruit, where good storage design

permits a closely controlled and steady temperature. Experiments have shown a 20–25% improvement in keeping quality of apples stored at –1.0°C rather than at 0°C (148). Depending on growing conditions, a few cultivars such as Jonathan, Northwest Greening, Grimes Golden, Cox Orange, and Winter Banana may develop soft scald and sometimes soggy breakdown at temperatures below 1–2°C (39). Coreflush (core browning) of McIntosh and internal browning of Newtown are associated with low temperature. Storage of McIntosh at –1 to 0°C for 3–4 months or more regularly results in core browning. CA storage at 2–4°C has been highly effective in preventing core browning of McIntosh without accelerated ripening. Newtowns grown in the cool summer weather that prevails at Watsonville, Calif., and in the occasional cool summer in British Columbia require temperatures above 2.0°C to avoid internal browning.

Storage disorders of apples

Some of the storage disorders listed in Table 3, which can be modified by handling and storage practices, are discussed briefly here, and the references supply more detailed information (39, 42, 49, 60, 140, 159).

Storage scald. All apple cultivars develop scald under certain circumstances. However, some cultivars such as Spartan, Golden Delicious, Newtown, and McIntosh seldom develop the disorder during the normal storage span. The incidence of scald in the more susceptible cultivars varies with season, cultural practices, and handling procedures. Hot weather before and during harvest, immaturity, high fruit nitrogen, delays in storage, high storage temperature, and extended storage periods all tend to increase scald (39, 63). Waxing and storage in polyethylene-lined boxes sometimes increase scald. CA and low O_2 storage reduce scald (88, 99, 134).

The comments above suggest obvious ways in which the grower and storage operator can reduce a tendency to scald, but for the cultivars grown where scald is likely to occur it is advisable to treat the fruit with chemical scald inhibitors within 4 or 5 weeks of harvest and, preferably, immediately after harvest before cold storage. Two effective scald inhibitors are permitted for use on apples (68, 157, 179), although their continued use is under review. These are ethoxyquin, sold under the Monsanto trade name of Stopscald®, and diphenylamine, commonly called DPA. DPA is usually considered to be the most effective, but both are much better scald inhibitors than oiled wraps. DPA should not be used on Golden Delicious apples or Anjou pears, and it sometimes causes injury to other varieties. Stopscald® has few limitations in its use and has caused injury only when fruit has been allowed to remain in liquid such as in the concave bottoms of

fruit containers not provided with suitable drainage holes. Stopscald® is most effectively applied by complete immersion of the fruit in the container or by a cascade of a high volume of liquid into the container. Providing it is allowed to dry after Stopscald® has been applied, the fruit can be washed or waxed without impairing the effectiveness of the scald inhibitor (157). Stopscald® also can be applied as a fine spray and brushed on the fruit during the packing operation. Although this procedure provides excellent scald control, it is not used frequently because some workers may develop dermatitis from contact with the chemical.

Coreflush. Coreflush, or core browning, a common storage disorder of McIntosh wherever the cultivar is grown, is associated with low storage temperature and senescence (39, 148). The disorder, which is accentuated by immaturity and excess fruit nitrogen (42), generally appears in McIntosh after 3–4 months' storage at –1 to –0°C and is intensified by a further 5–6 days at 21°C. Experimentally, coreflush and scald have been reduced by gamma irradiation (140), but the only practical method of avoiding coreflush in McIntosh is to use CA storage, which permits higher temperature without excess ripening. In the Okanagan Valley of British Columbia, CA McIntosh apples are stored at 1.5–2.0°C, the minimum temperature for control of coreflush (155). In other McIntosh-growing areas, it appears necessary to use temperatures of at least 3°C in CA to avoid coreflush.

Breakdown. Except perhaps for the variety Jonathan, which sometimes is affected by low temperature, breakdown losses of consequence are from the senescent type of the disorder. In this form of the disorder, affected tissue is typically soft, dry, and mottled brown. In general it is associated with high fruit nitrogen, large fruit, overmaturity, accelerated ripening as a result of poor handling and storage practices, and Ca deficiency, which may or may not be associated with high magnesium (Mg) content. With certain cultivars, such as Golden Delicious, Spartan, and McIntosh, breakdown may develop as a result of bruising. In other cultivars, such as Delicious and Winesap, breakdown is often associated with water core. Although CA storage delays senescence and breakdown, it is not the best remedy for basic problems arising from poor culture and handling practices. Breakdown of Spartan associated with Ca deficiency can be controlled by foliar sprays or postharvest dips of calcium chloride ($CaCl_2$). Losses associated with water core can be minimized by timely harvesting by the alert grower. Delicious apples with water core can be separated by an alcohol solution of suitable specific gravity (156). A slight to moderate amount of water core, particularly if the affected tissue is not consolidated in one area of the apple, is dissipated in cold storage with few adverse effects. Holding harvested

apples at prevailing orchard temperatures to accelerate disappearance of water core is a poor practice that hastens ripening and the onset of breakdown and precludes effective separation by differential flotation in alcohol solutions.

Decay. Losses from decay, usually caused by *Penicillium* but in some cases by *Gloeosporium* or *Botrytis*, often relate to cultural and handling practices. Since the inoculum is ever present, apples may be infected with *Penicillium* as a result of rough handling that causes skin breaks and bruises. The increasing use of immersion dumpers also increases the chances of infection in damaged fruit. Perennial canker of apple trees is a source of *Gloeosporium* infection, which occurs in the orchard, develops slowly in fruit during cold storage (44), and is not inhibited by low O_2 atmospheres. Wet harvest weather and prolonged storage at high humidity are conducive to the development of this pathogen. Thiabendazole and benomyl are effective decay control materials and have been registered for postharvest use on apples and pears. These chemicals applied as postharvest dips or sprays have given good control of *Penicillium*, *Botrytis*, and *Gloeosporium*. Benomyl, however, may cause russetting of sensitive varieties. Where scald protection is needed and a fungicide is considered necessary, a mixture of Stopscald® and a fungicide can be applied simultaneously.

APRICOTS

Temperature: –1.0 to 0.0°C
Relative humidity: 85–95%

Apricots have a short storage life, depending on the cultivar and on harvest maturity. Mature soft fruit usually has a maximum 2-week storage life, whereas firm, well-colored fruit can be stored for 2–4 weeks. Deterioration of flavor, increased tendency to decay, and failure of ripening capacity limit the storage life of apricots. Picking and storing fruit in a less mature green condition accentuates these weaknesses. A phenomenon peculiar to apricots and peaches in cold storage is the development of a dry, woolly texture. This can occur in fruit that is immature and overstored at low temperatures. The onset of woolly texture can be prevented and the cold storage life of apricots extended to 5–6 weeks by periodic warming of the fruit (48 h at 20°C every 2–3 weeks of storage) or by CA storage [3–5% CO_2 plus 2–5% O_2 at –1 to 0°C; (31, 202)]. For optimum storage results apricots should be picked as mature as handling and packing procedures permit. To prevent brown rot in storage caused by *Monilinia* spp., apricots should receive a postharvest dip or spray of benomyl applied as soon as possible after harvest.

BLUEBERRIES

Temperature: 0°C
Relative humidity: 85–95%

Most blueberries are not precooled but are graded and packed immediately after harvest and shipped under refrigeration at 10°C. Fruit that is handled this way has a postharvest life of 1–3 days, which is the main reason for choosing air freight to ship fruit to distant destinations. Blueberries are very susceptible to attack by *Botrytis cinerea, Alternaria* spp., and *Gloeosporium* spp., which usually terminate commercial storage or shelf life. However, blueberries that are harvested with stems intact, have a low sugar-to-acid ratio, receive a surface sterilant or fungicide application, and are precooled within several hours of harvest and stored at 0°C can have an acceptable storage life of 2–4 weeks (8, 29, 74, 76). CA storage using 20% CO_2 and 15% O_2 (29) can provide modest additional storage life.

CHERRIES

Temperature: –1.0 to 0.0°C
Relative humidity: 85–95%

Sweet cherries have a cold-storage life of about 3 weeks, sour cherries only a few days. Storage life of sweet cherries depends to a considerable extent on the treatment of the fruit after harvest. Because cherries have a large surface-to-volume ratio, moisture loss may be rapid, particularly if temperatures after harvest are high. Under hot, dry conditions cherries may lose weight at a rate of 1%/h, whereas their stems could lose weight at 4%/h (133). To avoid excessive darkening of color, browning of stems, and deterioration of appearance, harvested cherries should be protected from the sun and delivered to the cold storage within several hours of picking.

Cold storage of cherries in sealed 38-µm (1.5-mil) polyethylene box liners, which results in an atmosphere of 6–9% CO_2, is effective in maintaining a fresh appearance and preventing decay during extended storage. Although cherries are tolerant of high carbon dioxide and low O_2 levels, polyethylene liners must be slit open when the fruit is removed from cold storage. The storage of sweet cherries in atmospheres containing 20% CO_2 plus ambient O_2 levels at –1 to 0°C reduces decay, stem browning, and firmness loss and can extend total storage life up to 5–6 weeks (133). Storage of cherries in a variety of CA environments is no more successful than storage in sealed polyethylene liners (154). However, sweet cherries stored in very low O_2 (0% CO_2 + 1.0–2.0% O_2, –1.0°C) can retain fruit firmness, titratable acids, and fresh green-stem appearance, and their storage life can be extended to 5–6 weeks (30).

The storage life of cherries is often terminated by decay, which may increase rapidly when the fruit is moved from cold storage to warmer conditions. Dichloran is effective in suppressing decay and can be used where sweet cherries are hydrocooled or handled wet during sizing and packing. Cherries that are packed wet must be cooled promptly and effectively to avoid splitting. Both sweet and sour cherries can be sprayed with the fungicide iprodione 1 day before harvest to reduce brown rot decay in storage caused by *Monilinia* spp.

For maximum storage life, shelf life, and resistance to mechanical damage (101), black cherry cultivars (Bing, Hedelfingen, Lambert, Sam, Ulster, and Van) should be harvested when they reach a red to maroon color (cherry color comparator Nos. 6–33) (25). Sweet cherries harvested for processing should be left on the tree until fully black (color comparator No. 34). Recently, the trade has expressed a preference for lighter colored fruit (color comparators Nos. 3–6), which is based solely on the marketing pressure to take advantage of early, high-priced markets. Although this trend may increase early returns, consumers are presented with low-quality fruit (48) (high acid and low soluble solids) that is susceptible to mechanical damage (101). Subsequently, it is difficult to maintain the price of the product and consumer demand for high-quality fruit harvested after the initial harvesting period. Fresh green stems are considered indicative of cherry condition. Prompt cooling after harvest, packing in polyethylene liners, and the application of emulsifiable coatings (95) help to prevent water loss and preserve the fresh appearance of the fruit.

CRANBERRIES

Temperature: 2.0–5.0°C
Relative humidity: 80–90%

The storage life of cranberries is limited by the development of decay, shrinkage resulting from moisture loss, and physiological breakdown. Common, air-cooled storage can be used to keep cranberries for up to 2 months, but they should keep for 3–4 months with refrigerated storage at 2–5°C. Storage at 7–10°C for several weeks after harvest improves the color of cranberries, particularly early harvested berries. Storage at temperatures near 0°C for more than about 4 weeks may result in low-temperature breakdown. Physical damage imparted to cranberries during mechanical or rough hand-harvesting, transport, or mechanical sorting and packing significantly reduces shelf life and accentuates losses from decay and bruise-induced breakdown (57, 115, 135).

CA storage has not been effective in reducing cranberry breakdown (5), but exposure to 100% N_2 for 3 weeks can reduce decay (109). Berries stored in tight containers or unventilated storages may be injured by a buildup of CO_2 and a depletion of O_2.

GRAPES

Temperature: 0°C
Relative humidity: 85–95%

The Canadian grape crop is of the labrusca (American) type or the vinifera (European) type, with the labrusca having a shorter storage life than vinifera. The American type of grape is usually shipped directly to market for consumption or processing, and these grapes can be held for up to 4 weeks if a temperature of 0°C is rigidly maintained. Hybrid varieties such as Sheridan can be stored successfully for up to 2 months. Sulfur dioxide fumigation is likely to damage the American type of grape but not the European type. Careless handling makes grapes crack, and low humidity desiccates their stems (22, 70).

Vinifera grapes can be stored for periods of up to 4–6 months when the fruit is loosely packed and enclosed in polyethylene liners with a two-stage SO_2 generator at 0–1°C (71). Enclosure in 38-µm polyethylene liners prevents the desiccation of stems and fruit, but the high humidity promotes decay. The two-stage SO_2 generator retards the development of decay during long-term storage. The generator, which consists of 3 g potassium metabisulfate placed in a paper bag plus 3 g potassium metabisulfite in a 38-µm sealed polyethylene bag per 10 kg of fruit enclosed in an additional polyethylene liner, retards the development of decay during long-term storage (123).

MELONS

There are three main types of melon sold in Canada: cantaloupe, honeydew, and watermelon. The first two are botanical cultivars of muskmelon. Melons as a whole do not have a long storage life. However, by cooling, spoilage is delayed during transit and marketing, and temporary storage is made possible during times of market surplus.

Cantaloupe or muskmelon

Temperature: 0.0–7.0°C
Relative humidity: 85–90%

Cantaloupe usually has a storage life of about 2 weeks at 0°C, but under certain undetermined conditions, some cultivars may suffer from low-temperature breakdown below 7°C. Maturity, which affects both storage behavior and market quality, is determined by stem separation and color. Optimum harvest maturity is at the stage of full slip, when the stem separates completely and cleanly, and before yellowing has occurred. Such melons do not have as long a storage life

as less mature melons, but they have the advantage of higher quality (125). More mature cantaloupes can be stored safely at lower temperatures. Icing is often used as a means of cooling the melons. Cantaloupe should be inspected often and very carefully in storage and on the market to detect spoilage before it reaches serious proportions (162).

Honeydew

Temperature: 7.0–10.0°C
Relative humidity: 85–90%

This melon, which is subject to chilling injury, has an expected storage life of 2–3 weeks at 7°C. Disorders are similar to those of cantaloupe. It is considered somewhat hazardous to use ice for cooling melons other than cantaloupe (112).

Watermelon

Temperature: 2.0–4.5°C
Relative humidity: 85–90%

Watermelon has a storage life of 2–3 weeks at 2–5°C. If held at 0°C, pitting and objectionable flavors develop. The onset of decay is the factor that usually determines the end of storage life (162).

PEACHES

Temperature: 0°C
Relative humidity: 85–95%

Peaches usually have a cold storage life of up to 3 weeks at most, depending on cultivar, maturity, and fungus infection. When not terminated by decay, the storage life of peaches is often limited by the development of a dry, mealy texture, sometimes aptly described as woolliness. Late cultivars, cool growing conditions, and immaturity favor the development of mealiness in extended storage (50), which can be partly overcome by intermittent warming for 2 days at 20°C every 2–4 weeks (14). The tendency toward development of mealy breakdown, however, is much reduced by ripening susceptible fruit for 2 days at 21°C before cold storage. It is best to pick peaches 6–7 days before maturity and store them at 21°C for that time. Fruit that is much more mature may have good flavor but poor texture – soft, sometimes stringy, and subject to bruising. Fruit that requires 9–10 days for ripening is often astringent in flavor, low in sugar and cultivar flavor, small, and poorly formed. A temperature of 18–24°C at 50–65% RH is ideal for ripening peaches. A temperature of 27°C or

higher is likely to induce reddish discoloration of the flesh and off-flavors (186).

The cold storage life of some peach cultivars may be extended by CA with intermittent warming. Early studies indicated that 5% CO_2 plus 3% O_2 at 0°C is a suitable atmosphere for a number of peach cultivars (15, 112, 194). More recent studies (4) indicate that 5% CO_2 plus 1% O_2 at 0°C with intermittent warming to 20°C for 2 days every 4 weeks of storage may increase storage life to as long as 20 weeks.

Peaches are very susceptible to fungal decay in storage, often resulting in serious losses. Postharvest dips or sprays of dichloran effectively control *Rhizopus*, whereas postharvest treatments of benomyl are effective against brown rot caused by *Monilinia* spp. Brown rot in storage may also be reduced by an application of iprodione 1 day before harvest.

PEARS

Temperature: –1.0°C
Relative humidity: 85–95%

Despite their hard, indestructible appearance when they are picked, pears are a delicate commodity requiring special postharvest care (51, 64). A few extra hours in the orchard, slow cooling, or storage temperatures a little above optimum are primary causes of shortened storage life and consumer dissatisfaction. Storage of Anjou and Bartlett pears at –1°C instead of 0°C can increase storage life by 40% (151, 152). Cooling to –1°C within 4 days of harvest should be the objective where long storage is required. However, attempting to cool pears this quickly and to maintain –1°C temperature is not practical in storages that lack sufficient cooling coil capacity or air volume. Some Bartlett pears, when picked with a high starch content and a low sugar level, may have a freezing point as high as –2°C.

The pressure test shown in Table 4 is a fairly reliable index of maturity for pears. Bartlett pears, which mature in the warm weather of late August, are at the correct state of maturity for only about 1 week. Overmaturity reduces storage life and favors the development of core breakdown. Later cultivars, such as Anjou, which mature more slowly and sometimes drop, are more likely to be picked while immature. Immature pears often ripen unevenly and incompletely and are likely to have an astringent flavor. Pears reach harvest maturity while they are still hard and green and before they ripen on the trees. Checking the firmness of the flesh of pears with a pressure tester is a reliable means of assessing their maturity.

Cool night temperatures of about 7°C or lower in the latter part of the growing season can stimulate ethylene production and cause premature ripening of Bartlett pears on the tree. Under severe conditions, pears may ripen and develop breakdown before the normal

harvest. Moderately affected fruits show a pink color at the calyx (pink end) and are predisposed to breakdown during the ripening after storage. Research in Oregon has shown that the effects of preharvest chilling can be reversed by sprays of daminozide or gibberellic acid (63, 201).

Most cultivars of pear ripen more uniformly after 2–3 weeks in cold storage. In fact, some cultivars, particularly if they are not fully mature, require treatment with ethylene to induce ripening immediately after harvest. The ideal temperature for ripening is 18°C, but some cultivars, such as Anjou and Winter Nelis, ripen slowly in cold storage (7). Other cultivars, such as Bartlett, Bosc, and Flemish Beauty, fail to ripen in cold storage and if they are stored too long, they lose their ability to ripen at any temperature. Yellowing of Bartlett pears in cold storage is a sign that loss of ripening capacity is imminent. This condition may progress until the skin is a dark brown color referred to as scald. It is a senescent disorder and should not be confused with scald that may occur on Anjou pears, which is much like apple scald and can be prevented by the application of Stopscald® either as a dip after harvest or impregnated in fruit wraps.

Skin abrasion of pears during packing, transport, or handling causes unsightly brown marks that are the result of enzymatic browning of damaged epidermal cells. Because ripening makes fruit more susceptible to skin marking, pears should be packed when harvested or soon after they are placed in the cold storage. Cold fruit is not more sensitive than warm fruit to skin marking, and the practice of bringing pears out of storage to warm up before packing shortens storage life.

Pears are often packed in polyethylene box liners to reduce moisture loss and the likelihood of stem end shriveling during long storage. Liners of 38-µm polyethylene with multiple, fine perforations are used and are split open when pears are brought out of cold storage for ripening. The use of sealed film-liners to provide a CA type of environment has been unsatisfactory because high carbon dioxide levels often caused injury to the fruit. Tolerance of pears for the gas varies with the season, maturity, storage practices, and O_2 levels (64, 117, 195). Pears respond well to CA storage when CO_2 levels are kept below 2%. Risk of loss resulting from decay in pears packed in polyethylene or stored in CA can be minimized by prestorage treatment with the fungicide thiabendazole. Stopscald® can be combined with thiabendazole to prevent scald and rot on Anjou pears.

PLUMS

Temperature: 0°C
Relative humidity: 85–95%

The maturity of prune plums at harvest has a pronounced effect on their subsequent ripened quality. The most reliable indicator of maturity is their soluble solids content, as indicated by refractive index. Harvested prune plums having a 17–18% soluble solids content, by refractometer, ripen in about 7 days at 18°C, and after storage for 1 month at 0°C they ripen in 5 days at 18°C (47, 56). Color may also be used as an indicator; prunes are considered ready for harvest when their flesh color reaches a medium-dark amber. The pressure test apparently gives results that are too variable from year to year to be reliable (47, 56).

Triflora plums (Japanese type) are susceptible to breakdown, which is increased by storage at 0–4.5°C. Therefore, storage below 4.5°C is hazardous, but above this temperature storage life is relatively short. Other types of plums can be stored at 0°C, and the storage life at these temperatures is 2–3 weeks or slightly longer, depending on variety and maturity at harvest.

The chief disorders of plums, other than decay, are internal browning and breakdown. These disorders are not visible externally, and so frequent internal examination is necessary to avoid holding this crop beyond its marketable limit (112, 137).

RASPBERRIES

Temperature: 0°C
Relative humidity: 85–95%

Fresh raspberries, blackberries, loganberries, and dewberries are not adapted to long-term cold storage, but they benefit from the prompt removal from field heat (precooling). Raspberries can be held for a maximum of 5–7 days at 0°C and at 85–95% RH provided the fruit temperature has been reduced to 0°C within a few hours of harvest. Youngberries and boysenberries cannot normally be held longer than 2–4 days without significant losses (112).

Decay (*Botrytis cinerea*, *Rhizopus*, and *Cladosporium herbarum*) and fruit softening are the major contributors to a decline in the quality of raspberries and to commercial fruit losses. Rapid cooling after harvest retards berry loss, but preharvest $CaCl_2$ sprays (43), cultivar selection (33), and exposure to acetaldehyde vapor (160) further reduce losses to decay and fruit softening.

STRAWBERRIES

Temperature: 0°C
Relative humidity: 85–95%

Fresh strawberries can be held for a maximum of 10 days at 0°C and 85–95% RH. In storage, strawberries are likely to lose flavor and

brightness of color (112), but commercial storage life is usually terminated by the onset of decay (*Botrytis cinerea* and *Rhizopus*). If the temperature rises above 5°C, the growth of *Phytophthora* (leather rot) is accelerated.

Precooling (rapid removal of field heat) to 0°C is essential within 1–2 hours of harvest, because fruit maintained at 10°C has about one-third the storage life of fruit held at 0°C. Fruit not subject to precooling is often 25–30°C when brought in from the field and should be sold the same day. Precooling may be accomplished by forcing rapidly moving cold air through stacks of berries (forced-air cooling) before or after loading. Strawberries should always be transported and held under refrigeration near 0°C to attain maximum storage and shelf life.

Decay is a critical factor in limiting the storage life of fresh strawberries, and its control deserves special consideration if fruit is to be stored for any length of time. Preharvest (54) applications of captan, benomyl, iprodione, thiram, or thiophanate-methyl are effective in reducing postharvest losses to decay.

Cultivars that are characteristically soft also tend to be susceptible to decay (113). Selection of strawberry cultivars that are resistant to decay (33) but maintain the desired quality characteristics can extend expected storage life of strawberries. Exposure of fruit to 1–4% acetaldehyde vapor for 20–30 min (121, 161), dry ice, 20–30% CO_2 (dry ice in a polyethylene liner) (204), or CA (5–15% CO_2 + 1–2% O_2, 3°C) (207) can also reduce the incidence of decay and extend market life.

Gamma irradiation at 2–3 kGy has been effective in preventing decay of strawberries, which are one of the few commodities not adversely affected by this treatment (24). Legislation and costs have restricted the use of this technique, but limited commercial use of irradiation sterilization is imminent.

STORAGE REQUIREMENTS FOR VEGETABLES

Recommendations for storing most Canadian-grown vegetables are given in Table 5 and on the pages that follow.

ASPARAGUS

Temperature: 0°C
Relative humidity: 95–100%

Asparagus should be cooled to 0°C immediately after harvest and held at this temperature at very high humidity. Under these conditions, it can be stored for as long as 3 weeks. Because loss of moisture from the spears is difficult to control, the butts are often placed in water or in contact with damp moss, moistened paper towels

backed with waxed paper, or other sources of moisture. Temperatures higher than 0°C tend to promote growth, cause loose heads, and hasten the onset of woodiness or toughness. Because of these storage difficulties, asparagus is usually marketed directly after harvest and is placed in storage only as a temporary measure. If there is a long interval between harvesting and marketing, asparagus should not be held long at its destination. Under such circumstances precooling by forced air or hydrocooling (20–30 min at 0–5°C) before shipment is also beneficial. Two kinds of microbiological spoilage, bacterial soft rot and gray mold, can affect asparagus during storage, but they are effectively controlled by avoiding bruising and maintaining the temperature near 0°C (86, 102, 176).

Table 5. Recommended storage temperature, relative humidity, storage life expectancy, and highest freezing point of fresh vegetables (119, 206) (*continued*)

Vegetable	Temperature (°C)	Relative humidity (%)	Approximate length of storage	Highest freezing point (°C)
Asparagus	0	95–100	3 weeks	–0.6
Beans				
green or snap	7.0–10.0	90–95	8–10 days	–0.7
lima (shelled or unshelled)	0	90–95	2 weeks	–0.6
Beets, bunched	0	95–100	10–14 days	–0.4 (tops)
topped	0	95–100	1–3 months	–0.9
Broccoli (calabrese)	0	90–97	1–3 weeks	–0.6
Brussels sprouts	–0.5–0.0	95–97	1–5 months	–0.8
Cabbage, early	0	95–100	3–4 weeks	–0.9
late	0	95–100	3–7 months	–0.2
Carrots, bunched	0.0–1.0	95–100	2 weeks	
topped	0.0–1.0	95–100	4–9 months	–1.4
Cauliflower	0	95–100	0.5–4 weeks	–0.8
Celery	0	95–100	3 months	–0.3
Corn, sweet	0	90–100	8 days	–0.6
Cucumbers	7.0–10.0	95–100	10–14 days	–0.5
Eggplants	7.0–10.0	85–90	10 days	–0.8
Endive or escarole	0	95–100	2–3 weeks	–0.3

Table 5. **Recommended storage temperature, relative humidity, storage life expectancy, and highest freezing point of fresh vegetables (119, 206)** (*concluded*)

Vegetable	Temperature (°C)	Relative humidity (%)	Approximate length of storage	Highest freezing point (°C)
Garlic, dry	0	70–75	6–8 months	–0.8
Horseradish	–1.0–0.0	90–95	10–12 months	–1.8
Kohlrabi	0	95–100	2–4 weeks	–1.0
Leeks, green	–1.0–0.0	95–100	1–3 months	–0.7
Lettuce, head	0	95–100	2–3 weeks	–0.2
Mushrooms, cultivated	0	85–90	5 days	–0.3
Onions, dry	0	50–70	5–9 months	–0.3
green	0	95–100	2 weeks	
Onion sets	0	65–75	5–7 months	
Parsnips	0	95–100	2–4 months	–0.3
Peas, green	0	95–100	1–2 weeks	–1.2
Peppers, sweet	7.0–10.0	85–90	8–10 days	–0.7
Potatoes				
early crop	see text	85–90	1–3 weeks	–0.9
late crop	see text	85–90	see text	–0.9
Pumpkins	7.0–10.0	70–75	2–3 months	–0.8
Radish				
spring, bunched	0	95–100	2 weeks	–0.4
winter	0	95–100	2–4 months	–0.7
Rhubarb	0	95–100	2–3 weeks	–0.3
Rutabaga or turnip	0	95–100	6 months	–1.1
Salsify	0	95–100	2–4 months	–0.9
Spinach	0	95–100	10–14 days	–0.3
Squash, summer	7.0–10.0	70–75	2 weeks	–0.5
winter	7.0–10.0	70–75	6 months	–0.7
zucchini	5.0	95	1–2 weeks	–0.5
Sweet potatoes	13.0–16.0	85–90	4–6 months	–1.1
Tomatoes, ripe	10.0	85–90	3–5 days	–0.5
mature green	13.0–16.0	85–90	2–6 weeks	–0.8

BEANS, GREEN OR SNAP

Temperature: 7.0–10.0°C
Relative humidity: 90–95%

Snap beans, if cooled immediately after harvest and held at 7°C, can be stored for 8–10 days. Contact icing of snap beans should be avoided. If held at a temperature of 4.5°C or lower they are subject to chilling injury, evident as pitting in storage and russeting after removal from storage. Air circulation is important at all times. If the air becomes stagnant, moisture accumulates at the centre of the mass, hastening the onset of decay and other damage. The main forms of decay occurring in snap beans that are held too long are watery soft rot, slimy soft rot, rhizopus rot, gray mold rot, and anthracnose (102, 176). CA storage of green beans 0–10% CO_2 plus 2–6% O_2 (7°C) may extend postharvest life 3 days over air storage at the same temperature but is not considered to be commercially worthwhile (59).

BEANS, LIMA

Temperature: 0–4.5°C in pods; 0°C shelled
Relative humidity: 90–95%

Lima beans, when stored in the pod, have a storage life of approximately 2 weeks at 0°C or 10 days at 4.5°C. Good air circulation is as important as it is for snap beans, and the rot type of disorders are the same for both types of beans. Lima beans are often stored after shelling. If fresh, they can be held for about 2 weeks at 0°C or 4 days at 4.5°C. If they are held too long after shelling, they become sticky and their color fades (102, 176).

BEETS

Temperature: 0°C
Relative humidity: 95–100%

Beets are sold either with tops on or with tops removed. The former style is referred to as bunch beets and is primarily for the retail trade. The latter style is referred to as topped beets and is used for processing and, to some extent, for the retail trade. Bunch beets are often harvested before they reach full maturity (about 4–7.5 cm in diameter). They are not held in storage for long periods, although they can be held for 10–14 days at 0°C at a high relative humidity. Wilting and other damage to the tops can be lessened if beets are not crowded in storage. Sometimes the tops are lightly trimmed so that they do not look wilted. Icing before transportation to market helps to maintain a fresh appearance and longer shelf life.

Topped beets are more mature and are harvested in the fall before there is danger of freezing. Loose soil is removed, and the beets are topped by cutting close to the crown. All damaged and misshapen beets should be discarded. Irregular or coarse roots are likely to be tough and woody; damaged beets are likely to shrivel or be a source of infection in storage. Because beets have a strong tendency to shrivel, a high relative humidity should be maintained during storage. Under these conditions and at 0°C, beets may be held for 1–3 months. Root cellars and refrigerated storages are both satisfactory, and storage in ventilated barrels or slatted boxes is preferable to bulk storage (144, 163). CA has not been found suitable for the extended storage of beets (203).

BROCCOLI

Temperature: 0°C
Relative humidity: 90–97%

The storage life of broccoli is about 1–3 weeks under favorable refrigerated conditions. After this the buds usually drop off and the whole head becomes discolored. For even this short storage life broccoli requires refrigeration during transit and in the retail market. Continuous icing with crushed ice or liquid ice (consisting of 60% crushed ice and 40% water) or a steady temperature of 0°C is necessary to reduce wastage and loss of vitamin C. The most important types of spoilage are bacterial spot, bacterial soft rot, gray mold rot, and watery soft rot (162). CA may extend the storage life of broccoli by 1 or 2 weeks over that normally expected in cold storage (91, 105, 106). Broccoli is tolerant of low O_2 and high CO_2 atmosphere and develops injury symptoms only if O_2 falls below 0.5% and CO_2 levels exceed 20%. Optimum CA conditions (10% CO_2 + 1% O_2 at 3–5°C) have been shown to retard chlorophyll loss, flower bud senescence, and toughening of broccoli.

BRUSSELS SPROUTS

Temperature: –0.5–0.0°C
Relative humidity: 95–97%

Brussels sprouts are a short-storage crop, but they can be held for longer periods if harvested and stored on the main stem. Individually harvested, sprouts are usually stored no longer than 3–4 weeks at –0.5 to 0°C and a high relative humidity to prevent wilting. They should be stored in small containers to prevent yellowing and the development of mold. They suffer from the same disorders as cabbage and are best controlled by low storage temperatures with adequate air circulation (162, 184).

Brussels sprouts respond to CA (4–6% CO_2 + 1.5–3.0% O_2 at 0°C), retaining chlorophyll and having a lower incidence of decay than in air storage (105). Under ideal CA conditions, Brussels sprouts may have a storage life of 1–3 months.

CABBAGE

Temperature: 0°C
Relative humidity: 95–100%

Early cabbage, which is normally harvested during the summer, before the crop reaches full maturity, has a storage life of 3–4 weeks at 0°C and high relative humidity. Because this crop is usually grown for immediate sale, there is no great economic advantage in holding it for long periods in storage.

Late cabbage (winter white cultivars) has a storage life of 3–7 months, depending upon cultivar, when held at 0°C at a high relative humidity (Table 6). Although high humidity is required to prevent wilting, good air circulation is also necessary to prevent condensation

Table 6. Life expectancy of several cultivars of winter cabbage stored at 0°C*

Less than 3 months	3–5 months	5–6 months	Over 7 months
Danish Ballhead	Excel	Custodian	April Green
Eastern Ballhead	Quick-Green Storage	Evergreen Ballhead	Bartolo
Hitoma	Safekeeper	Green Winter	Decema Extra
Hybrid F	Superslaw	Storage Green	Hidena
Penn State Ballhead	Winterkeeper	Ultra Green	Houston Evergreen
Rio Verde			F_1 Mercury
Sanibel			Polinius
			Slawdena

*Add 1 or 2 months for CA [from Bérard and Vigier (17)].

in local cold spots, which favor mold growth. Late cabbage is harvested in the fall when it is fully mature, as shown by solid, heavy heads with a density of 0.72 to 0.80 $g \cdot cm^{-3}$, a weight of 2–3 kg, and a heavy waxy bloom on all the leaves, which gives them a steel-blue color. Harvested too early, cabbage loses excessive weight in storage through wilting, and harvested too late, heads are white and may have internal damage resulting from frost. At harvest the roots are trimmed fairly close to the base of the heads, and dead or damaged leaves are removed. At least one layer of healthy outer leaves should be retained to protect each head during handling and storage. Further trimming is usually needed when heads are removed from storage before marketing. The best storage is attained with shallow layers on top of slatted shelves or in bulk bins, but the heads can also be stored by piling them to a depth of not over 1.5 m if ample aeration, often by forced air, is provided within the pile or stack. Freezing should be avoided. Although cabbages show only slight external damage in response to light freezing, they freeze readily in storage at –0.8°C. The main disorders that occur in storage are caused by wilting, gray speck disease, vein streaking, black speck, and rots caused by *Botrytis cinerea*, *Sclerotinia*, *Alternaria*, and *Erwinia carotovora* (17, 18, 122, 162). Cabbage may be stored in CA (5% CO_2 + 2.5% O_2 at 0°C) for up to 10 months. This treatment is effective in preserving green color, maintaining succulence, and greatly retarding senescence (79). However, some tests show that cabbage becomes flaccid in CA storage with a catalytically generated atmosphere (55). A nonethylene gaseous by-product of combustion may be responsible for this condition, but the use of catalytic O_2 burners should be avoided for the CA storage of cabbage. CA storage may partly or fully control gray speck disease, black speck, and vein streaking (17, 18), but in some years it may aggravate the incidence of black midrib, necrotic spot, and susceptibility to frost injury (19, 20, 80).

Cabbage should not be stored with other products that generate ethylene. Accumulations as low as 1 ppm ethylene in cold storage may result in leaf yellowing and leaf abscision from the central stem. In CA however, ethylene accumulations may be neutralized by high CO_2 levels.

CARROTS

Temperature: 0.0–1.0°C
Relative humidity: 95–100%

For long storage, carrots are harvested when mature and after the leaves have assumed a slightly browned appearance. Harvesting in cool, cloudy weather to prevent drying of the roots from the time they are dug until they are placed in storage, and maintaining the relative humidity in storage at 95% or higher, will reduce the browning

disorders that often occur. During harvest, carrots are topped to retain the crown or top of the root, and objectionable roots are discarded. Coarse, damaged, distorted roots and the crease in the crown form focal points for subsequent decay. Care should be taken to avoid abrasion injury during harvesting, cleaning, and transport to the storage. Coarse particulate soils, rough, matted conveyor belts, or bristle cleaning brushes may injure epidermal cells and result in a white opaque surface injury, which is accentuated by low relative humidity. Properly matured carrots can be stored up to 3 m deep in bins if aeration, preferably by forced air, is provided. If stored in bulk storage provided with floor channels, carrots may be piled up to 4 m. Carrots to be stored in bulk should be prewashed, hydrocooled, and treated with an acceptable fungicide before storage. Carrots may alternative-ly be stored in bulk bins, ventilated barrels, or slatted crates for shorter periods. Most cultivars may be held for 4–5 months at 0°C. Adequate air movement and ventilation help to prevent bitter flavors caused by ethylene. Also, ethylene-producing fruits such as apples and pears should not be stored in the same area as carrots. High humidity is required to prevent shriveling or wilting, and on a small scale, carrots can be stored in damp moss, coarse sawdust, and layers of newspaper, sand, or other materials that control moisture loss (141). On a commercial scale, Filacell® and jacketed storages provide a high humidity but lack the ability to rapidly precool large volumes of the vegetable to 0°C.

More tender, immature carrots are harvested at less than 4 cm in diameter for immediate consumption or short storage. They are sometimes sold as bunched carrots with tops retained, but the tops may remove moisture rapidly from the roots and are prone to discoloration by yellowing. Therefore, even immature carrots are usually sold with tops removed. They may be packed in transparent film packages for the retail market or in crates for long-distance shipment. They should be hydrocooled to 4–7°C or lower soon after harvest and before packing for shipment. If shipped open in crates they can be top-iced or liquid-iced (slurry of 60% crushed ice in 40% water) to retain their freshness. The storage life of young carrots varies from several days to 2 weeks, depending on their age and storage conditions.

Carrots in storage may be damaged by severe freezing, although they do recover from a light frost (–1°C). They may also become shriveled through loss of moisture. Watery soft rot or bacterial soft rot may be prevalent toward the end of storage life. Discarding damaged or coarse roots at harvest helps to control these disorders, as do ventilation and frequent inspection during the storage period (176). Benomyl may also be used as a postharvest dip or spray to control a number of fungi that cause storage decays. Fungicides are often applied during the prewash, sorting, and hydrocooling operations before bulk storage.

Carrots have been stored for up to 15 months in self-generated MA of 3% CO_2 plus 17% O_2 at 1°C and 98% RH created by enclosing hydrocooled carrots in polyethylene 20 µm thick (139). However, most attempts to store carrots in CA have increased the incidence of decay in atmospheres containing more than 5% CO_2 or less than 10% O_2, with slight suppression of sprouting or rooting at 0–1°C (197) and partial retention of the carotene content (13).

CAULIFLOWER

Temperature: 0°C
Relative humidity: 95–100%

Cauliflower is not usually stored. If necessary, however, it can be held at a high relative humidity, for about 2 weeks at 0°C or 1 week at 4°C, provided the produce is placed in storage in good condition immediately after harvest. Cauliflower is usually packed in crates after it is harvested and trimmed. Heads may be placed downward to avoid damage by contact with water, soil, or other foreign matter, or alternatively they may be wrapped individually in cellophane, which would permit the heads to be packaged facing upward for presentation. Spoilage of cauliflower in storage may occur through wilting or if white curds in the heads mature and turn brown or start to grow so that they have a ricey appearance (162). Losses of the produce to decay are usually the result of *Alternaria* spp. or *Pseudomonas maculicola* infections, which appear as small brown or black spots that become enlarged to form large black lesions. These disorders are effectively inhibited by low temperatures. Thus, rapid precooling or the application of crushed ice, snow, or liquid ice before transit is strongly recommended (112).

Tests in Britain have indicated that the storage life of cauliflower may be extended by 2 weeks with the use of CA storage. The conditions suggested are 10% CO_2 plus 11% O_2 and 79% N_2 at 0–1°C. Alternatively, a maximum storage life of 8 weeks may be realized for cauliflower using 2–5% CO_2 and 2–5% O_2 at 0–1°C (82, 210), although the benefits to quality of CA storage as compared with optimal cold storage appear to be marginal.

CELERY

Temperature: 0°C
Relative humidity: 95–100%

Celery, if cooled rapidly after harvest and held at 0°C and high RH, has a storage life of approximately 3 months. Because celery is extremely prone to wilting, rapid cooling after harvest is essential. Immersion in ice water and other forms of hydrocooling either before

or after packing in crates have been found most satisfactory (146). Vacuum cooling is also helpful, as long as celery is fully wet. Top icing with either crushed ice or liquid ice (slurry of 60% crushed ice and 40% water) is particularly beneficial before transit.

Freezing damage has been reported at temperatures as high as –0.3°C (92). However, temperatures below 1°C are needed to prevent the growth of rot organisms in storage. It is absolutely essential, therefore, that precise temperatures be maintained. Because of the leafy nature of the crop and its fairly high rate of respiration, special attention to stacking in storage rooms is necessary to maintain uniform temperatures. Spaces for air movement both vertically and horizontally are needed between crates, and the celery should be trimmed flush with the top of the crates.

Some storage disorders such as soft rot, mineral deficiencies, and root rot have their origin in the field. To prevent the development of these disorders, it is helpful to have a knowledge of the conditions under which the celery was grown and to inspect the celery going into storage. Close scrutiny of celery during storage is advisable (176).

High relative humidity (98–100%) in storage created by jacketed or other storage systems significantly retards the rate of quality loss in storage (92). Moisture retention and quality have been improved by storing celery in vented or sealed 38-µm polyethylene crate liners at 0°C. The use of sealed liners, resulting in a 2–3% CO_2 concentration, has no adverse effects and helps retain green color (131). CA storages containing 5% CO_2 plus 3% O_2 have been shown to delay the development of decay and improve chlorophyll retention in celery (120, 199). However, the maximum extension of storage life using CA as compared with optimum high humidity air storage at 0°C may be an additional 2–3 weeks.

CORN, SWEET

Temperature: 0°C
Relative humidity: 90–100%

Sweet corn has a maximum storage life of 8 days if cooled and stored under optimum conditions. It should be harvested at the milk stage (when the juice from the kernel is milky in appearance) and cooled as rapidly as possible. Hydrocooling by spraying or immersion in water at temperatures near 0°C is most effective (83, 185). Vacuum cooling and air cooling can also be used if corn is moist. The main purpose of cooling is to retain the original flavor and succulence of the corn. But these qualities are lost through normal reactions that involve, in particular, the conversion of sugars, principally sucrose to starch. Because these reactions proceed more rapidly at high temperatures (about six times as quickly at 20°C as at 0°C), it is important to cool corn as quickly as possible (35).

When shipped to market, sweet corn should be precooled to 0°C within 6 h of harvest or copiously iced, and care should be taken to have the ice in contact with as much of the corn as possible. Because the insulation afforded by the husk and the cob tends to withhold the heat of respiration, a certain amount of air circulation within the stack is also recommended. These conditions are most easily attained if corn is packed in crates, the 5-dozen size being most common (174).

Further information on sweet corn is given in reference 77.

CUCUMBERS

Temperature: 7.0–10.0°C
Relative humidity: 95–100%

Cucumbers have a storage life of only 10–14 days at 7–10°C and high RH. They are sensitive to temperature. Below 7°C chilling injury develops, as evidenced by surface pitting and dark water patches; this injury is followed by the onset of rots, particularly when the temperature is raised. Chilling injury may occur in 2 days at 0°C, whereas rapid yellowing develops at temperatures above 10°C. Yellowing is accelerated by ethylene from such produce as tomatoes, apples, and peaches. Therefore, it is important that cucumbers be cooled quickly to 7–10°C and that they be held at this temperature during storage or transit. Slatted crates permit good air exchange and are recommended. Cucumbers are sometimes waxed to reduce moisture loss, which occurs readily (69).

Storage of greenhouse salad types of cucumbers in CA containing 0 or 10% CO_2 plus 3–5% O_2 at 10–13°C may extend the useful marketing life by 1–2 weeks over that of cold storage (6, 120). The beneficial quality response to CA may be enhanced by the removal of ethylene from the storage, which may provide up to 45 days of total storage-life expectancy.

EGGPLANT

Temperature: 7.0–10.0°C
Relative humidity: 85–90%

Eggplant cannot be expected to keep satisfactorily in storage for more than about 10 days. The optimum storage temperature is 10°C or slightly lower. Chilling injury in the form of slight surface pitting and bronzing, especially near the stem, has been noted at temperatures of 4°C or lower in 4–8 days. The pits sometimes occur in groups and coalesce into larger sunken areas on longer exposure (164).

ENDIVE OR ESCAROLE

Temperature: 0°C
Relative humidity: 95–100%

Endive or escarole is a leafy vegetable that, under commercial conditions, is not adapted to long storage. Even at 0°C, which is considered to be the best storage temperature, it cannot be expected to keep satisfactorily for more than 2–3 weeks. The storage requirements for endive are practically the same as for lettuce. As with lettuce, the use of crushed ice extends its storage life. The relative humidity must be kept at 95–100% to prevent wilting. A certain amount of desirable blanching usually occurs in endive that is held in storage (112), but when overaged, some browning occurs at the leaf base.

GARLIC

Temperature: 0°C
Relative humidity: 70–75%

Garlic is best stored under conditions of temperature and humidity recommended for onions. Garlic should be well cured before going into storage, and if it is in good condition, it should keep for 6–8 months at 0°C. Sometimes garlic is stored in common, air-ventilated storages; under these conditions, if kept cool, dry, and well ventilated, it may be held for 3–4 months or longer, depending on the temperature. Garlic is usually stored in loose mesh bags that are piled two layers deep in stacks separated by air spaces (112).

HORSERADISH

Temperature: –1.0 to 0.0°C
Relative humidity: 90–95%

Horseradish keeps satisfactorily for 10–12 months at 0°C and at 90–95% RH. Roots dug when the plants are actively growing do not keep as well as roots that have been conditioned by cold weather before digging. Frequent inspection is advisable (112).

KOHLRABI

Temperature: 0°C
Relative humidity: 95–100%

Kohlrabi should keep 2–4 weeks if stored at 0°C and 95–100% RH.

LEEKS, GREEN

Temperature: –1.0 to 0.0°C
Relative humidity: 95–100%

Green leeks are packed in crates and stored under conditions similar to those suitable for celery. If properly handled, they should keep satisfactorily in storage for 1–3 months. Packaging in sealed film bags is suggested (112), as reports indicate that leeks can tolerate up to 16% CO_2, which retards yellowing and rotting. Leeks can be stored for up to 6 months in 5% CO_2 plus 1% O_2 at 0°C and 98–100% RH, whereas the storage life of leeks in air at the same conditions is limited to 12 weeks or less.

LETTUCE

Temperature: 0°C
Relative humidity: 95–100%

Although there are several types, much of the commercial lettuce is of the crisp head type. Lettuce is not a long-storage crop, but if its temperature is reduced rapidly to 0°C and held at this level while the humidity is kept very high, head lettuce can be stored for 2–3 weeks or possibly slightly longer. Good temperature control is necessary if 0°C is to be maintained without freezing. Lettuce has been observed to freeze at temperatures as high as –0.2°C (112). Packing lettuce in individual perforated polyethylene bags or crate liners reduces moisture loss during storage and shipment.

Hydrocooling in ice water and icing in storage help to retain freshness and are most effective if done immediately after harvest and trimming. All damaged lettuce, particularly any affected with tip burn, should be discarded. This disorder leads to breakdown and to slimy rots in storage (163).

Vacuum cooling has produced revolutionary changes in the handling of lettuce in specialized growing areas. Large quantities of lettuce in boxes or crates are placed in a chamber, which is then evacuated to cause evaporation of the water inside and adjacent to the lettuce, producing rapid cooling. Because containers remain dry when cooled in this manner, fiber containers may be used, and rots are reduced during transit and marketing (9, 10).

Lettuce should not be stored with fruits such as apples, pears, peaches, or melons, which produce ethylene. Small concentrations of this gas cause yellowing and russet spotting. Low O_2 atmospheres prevent russet spotting, but CO_2 at levels of 4% and low temperature may cause brown stain in some cultivars (26, 104). There is good potential for CA storage of head lettuce for up to 75 days in 2.5% CO_2 plus 2.5% O_2 at 2°C (175).

MUSHROOMS, CULTIVATED

Temperature: 0°C
Relative humidity: 85–90%

Fresh mushrooms do not keep well and are therefore stored for only short periods. Deterioration is marked by brown discoloration of surfaces and by opening of veils. Freshly picked mushrooms keep in prime condition at 0°C for 5 days, at 4°C for 2 days, and at 10°C for only 1 day. Allowing a marketing period of only 1 day at higher temperatures immediately after storage, they should be kept at 0°C for only 3–4 days and at 4°C for up to 2 days. When they are being transported and displayed for sale, mushrooms should be kept under constant refrigeration (112).

Veil opening and mushroom deterioration can be prevented by CA combinations of 5% CO_2 plus 1.0% O_2 at 0°C or 50% CO_2 plus 10–20% O_2 (187). However, the effects of these CA conditions on microbial load on the product should be determined as safe before any commercial trial is attempted.

ONIONS

Three forms of onion are kept in storage: green (small, bunched) onions, dry onions (cured full-size bulbs), and sets (small cured bulbs sold in the dry state for planting purposes). Cured full-size bulbs are the main type held in storage.

Dry (or cured) onions

Temperature: 0°C
Relative humidity: 50–70%

Botanically the onion is a biennial; the first year it produces a bulb, the second year, flowers and seeds. The object of storage is to prevent even the slightest form of growth within the bulb. During early storage, the bulb is in the resting state and incapable of growth, but after 3–6 months it changes from this state and enters a critical period in its storage life when both internal and external symptoms of growth may develop. Storage at a high humidity stimulates root growth, and slight rises in temperature during this period hasten shoot growth. Even the internal development of sprout growth reduces quality and eventually terminates storage life. Thus the storage life of dry onions may be about 5 months, depending on cultivar, temperature control, and other factors (209).

However, if treated with a sprout inhibitor, such as maleic hydrazide or gamma irradiation, before going into storage, onions remain in the resting state for extended periods (73, 124). Thus, their

storage life may be extended to as long as 8–10 months, depending on such factors as the effectiveness of the sprout inhibitor treatment, the cultivar of the onion, the presence of disease, and the curing procedure used. (*Important*: Refer to the legal regulations that apply to the use of sprout inhibitors in your area before using them.)

Onions are harvested at maturity, when at least 50% of the stems have bent down to the ground. They are dug and topped and may be left in the field for curing; brittleness of skin and contraction of the neck indicate completion of curing. However, it is preferable to move the onions, after topping, to a storage-curing room. Here they are piled to a depth not exceeding 4.5 m and air is forced through the pile. The circulation of 1.5 m^3 of air per minute for each cubic metre of onions has been found satisfactory; unheated outside air is used for the first 2 days followed by air at 24–30°C (at the source of heat) with 60% RH for 8–10 days and, finally, by outside air to cool the onions before they are placed in storage at 0°C. Alternatively, where neck rot caused by *Botrytis allili* poses a problem, onions may be cured by raising the room temperature to 45°C over 5 or 6 days and holding the product at that temperature for 1 day, followed by cooling to the final storage temperature in 2 or 3 days. For a 700-t storage, this technique would require three oil-burning heaters operating at 160 000 kcal/h, with an approximate air circulation rate of 20 000–40 000 m^3/h through the product (138). About 5% of the onion weight has to be evaporated, and completion of curing is indicated by a well-contracted neck and brittle skin. Overcuring causes loss of skin. Excessive humidity or, perhaps, high temperatures cause staining of the skin. The latter effect may also result from moisture condensation on the surface of the bulbs, as sometimes happens when outside air on a warm day is brought into contact with onions at a lower temperature, that is, when the onion temperature is below the dew point of the outside air.

Onions are classified by shape and color, the yellow globe types making up the major portion of commercial stocks. Some cultivars of this type that are popular in Canada are Abco, Aries, Autumn Spice, Canada Maple, Copra, Capable, Cobra, Exporter, Progress, Rocket, and Taurus. The appearance of each variety is influenced largely by the method of curing. Air curing in a building results in the most uniform color and condition of the bulb. Curing to the correct level of moisture keeps the skin intact and gives it a bright appearance (35, 78, 209).

Green onions

Temperature: 0.0°C
Relative humidity: 95–100%

Onions in this form have a short storage life. Rapid precooling, hydrocooling, crushed icing, or liquid icing can be used to retain freshness. When treated in this manner, green onions can be held for up to 2 weeks.

Sets

Temperature: 0°C
Relative humidity: 65%

Onion sets are usually stored in common, air-cooled storages. Because of their small size they are stored in shallow, slatted trays to provide ample air circulation. If piled to any depth, the onion sets tend to pack tightly, prohibiting air movement. Otherwise they require the same storage treatment as dry onions.

PARSNIPS

Temperature: 0°C
Relative humidity: 95–100%

Parsnips are usually handled in the same way as carrots, and their storage life is 2–4 months at 0°C and high relative humidity. They are topped at harvest and can be stored in bulk piles, but more often they are stored in bulk bins, boxes, or other containers. Perforated polyethylene liners in the containers help to prevent moisture loss. The main storage problems with parsnips are surface browning and a tendency to shrivel as a result of moisture loss. Surface browning results from mechanical damage and rupture of the epidermal cells. This disorder can be prevented by careful harvesting and packing procedures to eliminate root damage.

PEAS, GREEN

Temperature: 0°C
Relative humidity: 95–100%

This crop is similar to corn in that the most likely form of quality deterioration is through normal reactions involving the conversion of sugars to starch. If possible, peas should be stored in the pod and cooled immediately after harvest by icing or immersion in ice water. Stored at 0°C, they may be held 1–2 weeks. At 4°C their storage life is about 3–4 days. Processing plants may have to store shelled green peas. The storage life of peas in this form is much reduced, but it can be extended by prompt cooling, hydrocooling, and washing to remove surface juice (112) and by transport and storage at 0°C.

PEPPERS, SWEET

Temperature: 7.0–10.0°C
Relative humidity: 85–90%

Peppers have a storage life of 8–10 days at 7–10°C. Red color and decay develop rapidly at higher temperatures. After a few days at 0–2°C, low-temperature injury in the form of surface pitting and decay causes serious damage upon removal of the peppers to room temperature (164). Packaging in perforated polyethylene bags and waxing extend storage and shelf life of green peppers (69).

POTATOES, EARLY CROP

Temperature: see below
Relative humidity: 85–90%

Early crop potatoes are harvested before they reach full maturity. They are used for immediate consumption and are unsuited for long storage. However, they can be kept for several weeks if they are in sound condition. If they are intended for table use, potatoes can be stored at 10°C, but if they are held for processing, particularly for making potato chips, storage temperatures of 15–21°C are better. Whatever the temperature, the relative humidity should be 85–90% (112).

POTATOES, LATE CROP

Temperature: see below
Relative humidity: 85–90%

Most potatoes are harvested at the late crop stage. Time of harvest is determined by the maturity of the potatoes and the possibility of damage by low temperatures in the field. Maturity is difficult to define, but the objective is to allow potatoes to reach maximum dry-matter content (high specific gravity) and to induce toughening or setting of the skin. These conditions are most nearly achieved when the vines have been dead for about 2 weeks. Usually the tops have to be killed either mechanically or by chemicals, or in irrigated areas by water restriction. Top killing by chemical means is recommended when late blight infection is suspected (128).

Potatoes are often handled too roughly. This causes damage that results in several forms of loss, including loss of moisture, and increased susceptibility to disease and browning disorders. Injured and disease-infected potatoes should not be stored.

Curing potatoes before placing them in storage is an extremely important operation. The objective is to improve their storage properties by making their skin firmer and tougher. This reduces

subsequent moisture loss, increases resistance to disease, and helps them to recover from injury. The actual physiological processes involved are suberization and wound periderm formation. The first process is completed in about 2 days at 20°C, but the second is considerably slower (189). High temperature and humidity are required for both processes. Curing is virtually stopped at a temperature of 8°C or lower and requires 10–14 days at 13–16°C and very high (95% RH) humidity (128). However, if the presence of late blight is suspected, the curing period may have to be shortened to avoid accelerated development of the disease.

The physiology of the potato is influenced markedly by temperature. Following curing, optimum storage temperatures are determined by ultimate use of the crop, duration of storage, and sprout-inhibition treatment. Temperatures of 4°C and higher induce sprouting, whereas those below 10°C induce sugar accumulation and those below 2°C may cause low-temperature injury (166). These factors dictate the following temperature recommendations:

Seed stock. Storage life for 7–8 months or longer if held at 2.0–3.5°C.

Table stock. Short storage at 7.0–10.0°C or until sprouting is imminent. The same temperatures can be used for long storage if sprout inhibitors are also used, otherwise 4°C is required for long storage. Storage life is 4–9 months, depending on cultivar.

Stock for processing into potato chips. A temperature of 10°C in combination with sprout inhibitors is best. If stored at 4°C, costly reconditioning is necessary to prevent browning.

Stock for processing into French fries. A temperature of 4–10°C can be used because the problem of browning is not quite as important as with chips. Potatoes should be stored at high RH (85–90%) at all times. This requirement is particularly important at temperatures of 7°C and higher, when shriveling is most likely to occur.

Sprout inhibitors permit storage at 10°C, avoiding the formation of reducing sugars and the need for reconditioning. Maleic hydrazide (amine form), at a rate of 3 L in 880–1320 L of water per hectare, applied to the vines in the field 2 weeks after full bloom, has been found very effective (128). Isopropyl-*N*-(3-chlorophenyl) carbamate (CIPC) can be applied satisfactorily in storage if all cuts and bruises on the potatoes are thoroughly healed before application (27). Gamma irradiation, at a level of 85 Gy, using a cobalt-60 source, has been found to be effective (130). A possible increase in sugars as a result of irradiation is a disadvantage (28), which, however, has been shown to be temporary (32). A method found highly satisfactory in Britain and elsewhere is the use of a nonyl alcohol

(3,5,5-trimethyl-hexan-1-ol), which is applied directly to the stored potatoes by evaporating the alcohol into the ventilation system at a concentration of 1 mL/m^3 at an air-flow rate of 1.5 m^3/min per tonne of potatoes (28). (Important: Before any chemicals are applied, the legal aspects of their use should be considered.)

Most potatoes are stored in common, air-cooled storage, although refrigeration sometimes is used, mainly as an auxiliary source of cooling. Uniform air and temperature distribution are essential in maintaining good storage conditions. Otherwise, cold areas on the walls and ceiling of a storage room or in the stack itself may develop wet spots. If potatoes are piled in bins, the potatoes should not be higher than 4.5 m and the top of the pile should be kept level. A ridge at the top of a pile often provides conditions that lead to the formation of a wet spot. Although bags, boxes, and other containers are still used, bulk boxes or bulk storage are being used increasingly and make for economy in handling.

Light should be excluded from potato storages because it causes the production of chlorophyll (which gives the potatoes a green color) and the formation of solanine, a bitter, toxic compound.

The ventilation system and the insulation of storage buildings should provide adequate protection against low temperatures, particularly freezing during the winter. Conversely, admitting air that is at a higher temperature than the potatoes is likely to cause condensation (sweating). Ventilation should be sufficient to prevent the accumulation of CO_2, which can cause an increase in sugar content (72) or, possibly, blackheart under severe conditions (163, 165).

The potato-processing industry, and particularly potato chip manufacturers, are making special demands for the storage quality of potatoes. Dry-matter content, reducing-sugar content, and characteristics of texture are being checked closely. Proper selection of cultivars, careful handling, and adherence to proper storage management are the main factors contributing to high processing quality. If reducing sugars do accumulate, a reconditioning procedure consisting of exposure to 15–21°C for a week or longer permits them to be converted to starch or other compounds, or to be used in respiration. However, this procedure is often not effective for reasons not as yet completely understood. Soaking or washing the raw chips in water has been found to be effective (192). Cultivars having a reputation for suitability to reconditioning are Atlantic, Kennebec, Norchip, and Superior, but even these fail to respond to reconditioning on rare occasions. Further information on potatoes is given in references 16, 75, and 143.

Lougheed (110) found that storage of potatoes in 15% CO_2 at 10°C inhibited sprout growth; long-term storage in 2–5% O_2 appears to be promising for potatoes that are to be used for making chips. CA storage of potatoes is not recommended, however, as the improvement

in quality compared with proper air storage is not enough to justify the additional investment.

PUMPKINS AND SQUASH

Temperature: 7.0–10.0°C
Relative humidity: 70–75%

Pumpkins are a type of squash. The term pumpkin refers to the orange globular type of squash. The storage life of pumpkins and squash depends largely on their type and cultivar. In all cases, careful handling is important because injury to the skin is likely to lead to the development of rots in storage. Curing for 2 weeks at 26–30°C helps to heal minor injuries; this can be accomplished in the field or in a storage with stoves or other sources of heat. For maximum storage life, squash should be allowed to reach full maturity before harvest and the stems should be completely removed at harvest to avoid any risk of damage in handling.

After the squash has been cured, the temperature should be reduced to 6–10°C with 70–75% RH. Cultivars such as Table Cream and Butternut last for 2 months, Turban squash and Buttercup for 3 months, Delica and other Japanese types for 4–5 months, and Hubbard (hard-shelled squash) for 6 months. For best storage results, squash should be stored on slatted shelves one layer deep without touching each other. Pumpkins generally do not store as well as the other types of squash and are seldom held longer than a few weeks. Zucchini, a summer squash that has become extremely popular, is sold as harvested without curing treatment. Careful handling and protection against shriveling is required, since the skin is very tender and is susceptible to desiccation.

Summer squash (*Cucurbita pepo*) is harvested before it reaches full maturity. Its storage life is short, not exceeding 2 weeks. Summer squash is usually stored at 0°C and in 85–90% RH (112, 171).

RADISHES

Temperature: 0°C
Relative humidity: 95–100%

Spring radishes are usually marketed in the bunched form with tops retained. There is a trend, however, toward marketing topped spring radishes in plastic bags. Spring radishes have a storage life of about 14 days when held at 0°C and high RH. Their fresh appearance and marketability are improved by hydrocooling and ample icing before and during transit. Winter, or large, radishes keep in good condition for 2–4 months under storage conditions recommended for spring radishes (112).

RHUBARB

Temperature: 0°C
Relative humidity: 95–100%

Rhubarb stalks, if they are fresh and in good condition, can be stored for 2–3 weeks. Bunches should be packed in crates, which are stacked to allow ample air circulation on all sides; otherwise, there is a danger of heating and mold growth (112).

RUTABAGAS OR TURNIPS

Temperature: 0°C
Relative humidity: 95–100%

The Laurentian variety is most commonly grown and appears to be the most satisfactory for storage and for the market. It can be kept in good condition for up to 6 months at 0°C and 95–100% RH. There is a general tendency to disregard the need for careful handling during harvest operations. Those who practice careful handling, however, find that it pays off in the form of reduced rot and other injury during the storage period. The use of maleic hydrazide has been found to be effective in reducing sprouting when the crop is stored under less than optimal conditions. (*Important*: Before using any chemicals refer to the legal regulations that apply to their use in your area.) The rutabaga is usually stored in bulk, but bulk bins are preferred.

This crop responds well to waxing. If properly waxed, rutabagas lose less moisture and are more attractive. The waxing procedure, used after storage, has contributed largely to the high international reputation of Canadian rutabagas (53, 84, 129).

SALSIFY

Temperature: 0°C
Relative humidity: 95–100%

Salsify has the same storage requirements as topped carrots. The roots are not injured by light freezing, but they should be handled carefully while frozen. Under the conditions specified, they should keep for 2–4 months (112).

SPINACH

Temperature: 0°C
Relative humidity: 95–100%

Spinach is usually stored for short periods only. It should keep fairly well for 10–14 days after it is cut. If the spinach is precooled

rapidly and crushed or liquid ice is used in the packages, this period can be extended somewhat (112, 163).

SWEET POTATOES

Temperature: 13.0–16.0°C
Relative humidity: 85–90%

Sweet potatoes require long periods of warm weather for growth and high temperatures for storage. Low-temperature injury occurs in storage at temperatures below 10°C; this results in pitting, particularly if the sweet potatoes have not been cured, and in increased decay and discoloration, either before or after cooking.

At harvest, sweet potatoes should be fully mature and free from injury. For satisfactory storage, they should be cured for 10 days at 30°C with 90% RH or higher. Heating equipment and the addition of moisture are usually required for this operation. After curing, the temperature is reduced to 13–16°C with 85–90% RH. Under these conditions sweet potatoes should keep for 4–6 months (112).

TOMATOES

Temperature: ripe, 10.0°C; mature green, 13.0–16.0°C
Relative humidity: 85–90%

Tomatoes are usually harvested when green (mature green) or partly colored. The objective in storage after harvest is to control the rate of ripening. Temperatures below 10°C in the field or in storage may result in damage caused by chilling injury. At 10°C the rate of color change and the development of such effects as uneven coloring, pitting, breakdown, and poor flavors are much reduced (196, 208). This temperature effect is somewhat complex; under some circumstances no apparent damage occurs during short exposures to lower temperatures.

A temperature of 13°C is recommended for slow ripening. At this temperature most cultivars can be kept in good condition for 2–6 weeks and change color very slowly. At 15°C the rate of color change increases quite sharply (166), and above 21°C the rate of maturation and other changes are increased. Tomatoes held at 18°C change color rapidly without excessive softening. Temperatures of 21°C or higher induce rapid ripening and bring about changes in color, softening, and flavor.

When tomatoes are fully ripe, the holding time can be increased by reducing the temperature to 10°C. Some experiments have shown that ripe tomatoes can be held satisfactorily at 0–4°C. It has been shown, however, that some softening may occur at 2°C. Thus, it is generally considered hazardous to hold ripe tomatoes in storage for more than a few days (61, 173).

Ethylene has been used to increase the rate of ripening and particularly to bring about color changes. Although it has not been proved to be consistently effective for these purposes, tomato ripening may be accelerated by exposure to 300–400 ppm C_2H_4 at 20°C for the duration of the ripening period. For further information on tomatoes, see references 112 and 163. Field applications of benomyl have been shown to accelerate ripening, presumably by stimulation of ethylene production (188).

Quality retention and storage life of tomatoes have been shown to benefit from CA, depending on the cultivar stored (108). Optimum fungal control of *Phoma destructera*, *Alternaria alternata*, *Botrytis cinerea*, and *Fusarium* spp. was achieved with 2.5% CO_2 plus 2.5% O_2 at 13°C, whereas 5.0% CO_2 and 2.5% O_2 were optimal for Nova Scotia and Quebec cultivars (41). Commercial use of high CO_2 plus low O_2 atmospheres may be limited to MA created by enclosing a known weight of product within a differentially permeable membrane and allowing the produce to generate a beneficial atmosphere within a package (3).

REFRIGERATED STORAGE DESIGN AND CONSTRUCTION

GENERAL CONSIDERATIONS

When building a large cold-storage structure it is advisable to obtain detailed engineering plans and specifications for the structure and the equipment. This step ensures that contractors have an equal opportunity to submit tenders and provides protection for the owner. Although the information that follows may be of some use in developing cold-storage plans and specifications of this kind, it is offered more specifically as a guide for those building small cold storages without professional consulting services.

A number of useful publications relating to cold-storage construction (1, 58, 63, 132, 141, 168, 169) are available. Also, the Canada Plan Service has prepared plans for fruit and vegetable storages. A catalog of these plans may be obtained from provincial departments of agriculture or local extension advisers. The authors do not intend to present cold-storage construction in detail in this publication but to emphasize certain factors that are considered important to efficiency and economy. The storage should be designed to include some form of mechanical handling of produce in bulk bins or on pallets. The building will therefore have a cement floor on grade, will be free from supporting posts, and will have a ceiling height appropriate to the height of the stored produce. The method of storing must be considered in planning the size and shape of the storage.

In pallet storages, rows of containers should run parallel to the direction of air flow and should be spaced 12–15 cm apart. However, recent studies (12) have questioned the need for between-row spacing, provided that adequate air movement is present. A clearance of at least 25 cm should be provided between the pallets and the walls. Adequate clearance is needed for the return of the ventilating air and to reduce the effect external conditions have on the storage environment near the exterior walls. A good place to locate air ducts or blower coils is above the trucking aisle, which is usually along the centre line in a large storage or along one wall in a small storage.

It is necessary to allow at least 0.5–1.0 m of clearance between the top of the stored produce and the ceiling to permit air to flow to the exterior walls unimpeded by any structural feature. The velocity of air leaving the blower or duct should be enough to direct it to the farthest point in the storage; otherwise, cooling will be inadequate and temperatures will not be uniform, which may cause condensation on or freezing injury to the product.

INSULATION REQUIREMENTS

This discussion includes a few unavoidable technical terms, which are explained below.

Heat leakage. Field heat and respiration heat were defined at the beginning of this publication in relation to product cooling. Heat leakage is another heat source to contend with in the storage. Heat moves from a warmer to a colder zone, and the rate of heat transfer is proportional to the temperature difference and the resistance to heat flow. In a cold storage, the insulation and other building materials offer resistance to heat flow. In a well-built storage, the refrigeration load attributed to heat leakage is small in relation to that from field heat. Other sources of heat include electric lights, electric motors, forklifts, workers, and infiltration of warm air. The definitions that follow are related to heat and can be useful.

Thermal capacity. The quantity of heat required to raise 1 kg of water by 1°C is referred to as thermal capacity and is equivalent to 4.2 kJ (kilojoules).

Refrigeration load. The size of a refrigeration system is determined by the cooling capability required per unit time or refrigeration load. It is a measure of power required and is expressed as kilojoules watts per hour; 1 W (watt) is equivalent to 3.6 kJ/h.

Specific heat. Specific heat refers to the number of kilojoules that must be added to or removed from a substance to change the

temperature of 1 kg of that material by 1°C. Where the exact specific heat for a particular product is not known, a value of 3.8 is acceptable for most fruits and vegetables.

Heat transfer resistance values (R). The resistance to heat transfer through various building materials has been measured and is expressed as a resistance value (R), which is the number of kilojoules moving through 1 m^2 of material 1 cm thick in 1 h when the temperature difference is 1°C. For example, the R value for fiber glass insulation is about 0.002, for concrete 0.064, and for wood about 0.024–0.051. The larger the R value the better the insulation.

Average resistance to heat transfer (R). The average resistance to heat flow through an insulated wall can be calculated using the known R values for the insulation and structural components of the wall. The average insulating value (R value) of a composite floor, wall, or ceiling can be determined by multiplying the R value for each material by its thickness and then totalling all R values for each component material. For heat leakage calculations, there is an additional R value resulting from a surface dead air film, which must be included in the resistance calculations and which can be found in Table 7 (11). The factor expressing total heat conductivity of a composite structure, such as a floor, wall, or ceiling, is the inverse of the R value (1/R) and represents the heat (kilojoules) that will pass through 1 m^2/h for each degree (Celsius) of temperature difference between the warmer and colder sides.

The better the insulation (larger R value) the smaller the heat leakage. However, because of current energy costs, a point is reached where additional insulation cannot be justified. For a storage temperature of –1.0 to 0.0°C the R values of the floor, walls, and ceilings should be approximately 0.49, 0.95, and 1.6 ($m^2 \cdot °C \cdot h/kJ$), respectively (2).

Floors. Studies in the State of Washington (168) show that the cost of insulating the slab floor of a cold storage is not justified when the water table is below 3.6 m. However, with rising energy costs approaching 2–3 cents per joule (5–8 cents per kilowatt-hour), a minimum R of 0.49 $m^2 \cdot °C \cdot h/kJ$ for floor insulation is recommended (2). It is also important to insulate the foundation wall about 60 cm below the outside grade toward the footing with 5 cm of rigid insulation such as styrofoam or urethane. This insulation prevents excessive heat loss around the entire perimeter. When insulation is omitted from the floor, a vapor barrier can also be omitted. When floors require insulation, material with adequate compressive strength (for example, styrofoam or urethane) should be used with a vapor barrier beneath the insulation.

Table 7. **Resistance values to heat transfer for some insulating and building materials**

	R value* ($m^2 \cdot °C \cdot h/kJ$)
Insulation	
Fiber glass batts†	0.064/cm
Fiber glass, loose	0.049/cm
Fiber glass, board	0.077/cm
Cellular glass (Foamglas®)	0.055/cm
Styrofoam, extruded	0.096/cm
Styrofoam, beadboard‡	0.080/cm
Polyurethane, board	0.120/cm
Polyurethane, foamed-in-place	0.120/cm
Polyisocyanurate, board	0.136/cm
Building materials	
Fir plywood	0.024/cm
Fiber-board sheathing	0.051/cm
Particle board (Aspenite®)	0.036/cm
Gypsum board	0.017/cm
Concrete, cast	0.002/cm
Concrete block (20 cm)	0.054
Concrete block (30 cm)	0.063
Glass, single pane	0.005
Fire coatings for foam	
Perlite–gypsum plaster (1.25 cm)	0.013/cm
Vermiculite–gypsum plaster (1.25 cm)	0.012/cm
Fire-retardant cellulose (2.5 cm)	0.077/cm
Air film and air gaps	
Air film, outside summer or inside heated	0.012
Air film, outside winter or inside cold storage	0.008
2.5 cm or greater air gap (average value)	0.035

*Conversion factors: 1 W = 3.6 kJ/h; °K = °C + 273.
†Unfaced, average value for several types.
‡0.024 g/cm^3 density.

Vapor barriers. Insulating materials lose efficiency if they become wet. A vapor barrier on the warm side of the insulation (never on both sides) prevents movement of water vapor into the insulation and a buildup of moisture from condensation. One hundred to 120 µm polyethylene is an effective vapor barrier often used in frame structures where it is applied on the outside wall under the sheathing. Aluminum foil is also an excellent vapor barrier, but it should not be used in contact with concrete or soil because basic salts leaching from these materials soon destroy it.

REFRIGERATION REQUIREMENTS

With the foregoing information and the use of the data that follow, the refrigeration requirements of a fruit or vegetable storage can be calculated.

Produce load

The greatest source of heat to be considered is the sensible heat, or field heat, of the warm produce. It is important to have a realistic estimate of the amount of produce that will require cooling each day during the peak loading period. Heat from this source is calculated as follows.

Field heat of produce in kilojoules equals weight of produce multiplied by specific heat multiplied by temperature reduction. In addition, the heat from the container must be considered. Suppose, for example, apples at 21°C are being cooled to 0°C in 385-kg bulk bins; then for 40 bins handled daily the field heat in kilojoules will amount to 15 400 (actual weight of fruit in kilograms) × 3.8 (specific heat of apples in kilojoules) × 21 (the required temperature reduction in degrees Celsius) = 1 228 920 kJ/day or 51 210 kJ/h. One watt is required to absorb 3.6 kJ of heat per hour; therefore 14 225 W are required to cool the fruit contained in 40 bins.

The amount of heat originating from the bins is calculated by a formula similar to that used for the fruit: weight (about 1800 kg for 40 empty bins) × specific heat (about 2.5 for the bins) × the amount of required temperature reduction (21°C in this case). This works out to about 94 500 kJ/day for every 40 bins in this example (see Fig. 5).

Respiration heat

Respiration heat, or metabolic heat, is produced by all fresh produce and varies with the kind of produce, cultivar, maturity, and temperature. Because of the number of factors affecting respiration,

accurate values for heat of respiration cannot be given, but data in Table 8 provide fairly safe figures for calculating this heat source. These data show the great variation in respiration heat with various types of produce at various temperatures.

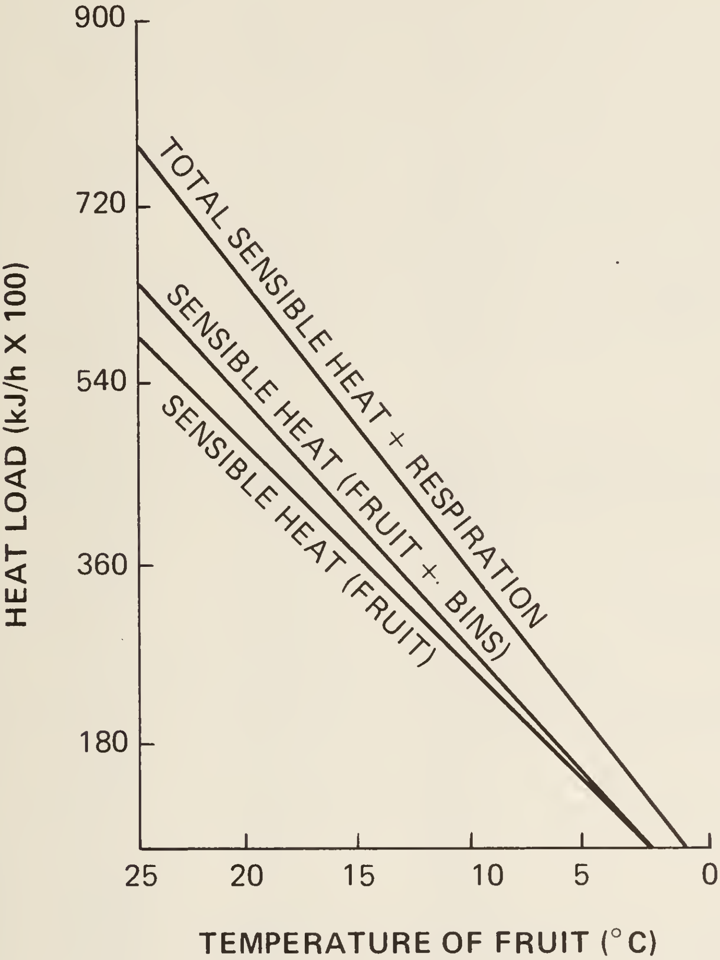

Figure 5. Heat load incurred by a daily loading rate of 40 bins of apples at temperatures between 0°C and 25.0°C and cooled to 0°C in 7 days. Content of bins (1.1 × 1.2 × 0.6 m) is equivalent to 385 kg net weight of fruit. If 20-kg boxes are substituted for bins, the sensible heat from the containers must be increased by a factor of 2.

Respiration heat for some types of produce at 0°C may be a minor consideration, but it must be accounted for when the produce is hot. The longer the time required to cool the produce, the greater the total

Table 8. Approximate rates of evolution of heat by certain fresh fruits and vegetables when stored at the temperature indicated*

	Rate of evolution of heat (kJ/t per 24 h)†			
Commodity	0.0°C	4.5°C	15.5°C	21.0°C
Apples	900	1 700	7 000	9 300
Asparagus	14 000	20 900	46 500	58 100
Beans				
green or snap	7 000	11 600	46 500	58 100
lima	3 300	5 800	29 100	40 700
Beets, topped	3 100	4 800	8 400	10 500
Blueberries	2 300	4 100	9 300	11 600
Broccoli, sprouting	5 100	19 800	58 100	79 100
Brussels sprouts	5 100	10 500	23 300	32 600
Cabbage	1 200	2 400	7 000	11 600
Carrots, topped	3 500	5 100	9 400	14 000
Cauliflower	4 200	5 200	11 600	14 500
Celery	1 900	2 800	9 500	11 900
Cherries	1 200	2 900	7 600	9 900
Corn, sweet	10 500	15 100	44 200	74 400
Cranberries	800	1 200	2 600	3 700
Cucumbers	1 900	2 900	7 000	9 300
Grapes, American	700	1 400	4 100	8 400
Lettuce, head	2 700	3 100	9 300	14 000
Lettuce, leaf	5 200	7 400	16 300	20 900
Melons (cantaloupes)	1 500	2 300	9 900	14 000
Mushrooms	8 100	17 400	53 500	73 200
Onions	600	900	2 800	4 200
Oranges	900	1 700	4 900	6 400
Peaches	1 500	2 300	10 500	19 800
Pears	1 000	1 900	11 600	14 000
Peas, green	9 800	17 400	48 800	69 800
Peppers, sweet	3 100	5 500	9 900	12 800
Plums	800	1 700	3 300	4 400
Potatoes, early	900	3 000	5 800	7 600
Potatoes, late	800	1 400	2 800	3 500
Raspberries	5 800	9 300	25 600	32 600
Spinach	5 200	12 800	44 200	53 500
Strawberries	4 400	7 000	23 300	30 200
Sweet potatoes	2 800	4 000	7 300	8 700
Tomatoes, mature green	700	1 300	7 200	9 300
Tomatoes, ripe	1 200	1 500	6 500	9 300
Turnips (rutabagas)	2 200	2 600	5 800	6 400

* Data developed from respiration studies and from other references, for example 1, 112, 119.

† Btu per ton per day x 1.16 = kilojoules per tonne per day.

respiration heat. For example, if apples are being cooled from 21.0°C to 0°C in 7 days and hot fruit is being loaded into the storage daily, the heat from respiration includes the cumulative respiratory heat of fruit at various temperatures between 21.0°C and 0°C. On the first day of loading, respiration heat would be relatively small, as it is produced by only 1 day's intake of fruit. On the seventh day, however, respiration heat approaches a maximum that persists with continuous loading. Table 9 was compiled from respiration measurements related to a typical cooling pattern in a fruit storage. It shows how respiration heat drops as fruit is cooled and that total respiration heat on the seventh day is a sum of the respiration heat of all fruit that has been stored. By adding values in the bottom line we obtain a total of about 17 800 kJ/t of fruit. During the loading period this figure becomes the basic respiration heat load, which increases only gradually as the storage is filled. For example, toward the end of the loading period, respiration heat would be 17 800 kJ/t of fruit loaded daily plus about 900 kJ/day for each tonne of fruit already cooled to 0°C.

Table 9. Cumulative respiration heat of apples during cooling produced when a tonne of apples are stored daily

Days from start of loading	Mean fruit temperature (°C)*							Total heat (kJ)
	15	10	6	4	2	1	0	
1	7000							7 000
2	7000 +	4000						11 000
3	7000 +	4000 +	2300					13 300
4	7000 +	4000 +	2300 +	1400				14 700
5	7000 +	4000 +	2300 +	1400 +	1200			15 900
6	7000 +	4000 +	2300 +	1400 +	1200 +	1000		16 900
7	7000 +	4000 +	2300 +	1400 +	1200 +	1000 +	900	17 800

*Approximate average temperature of the fruit during successive days as it is being cooled from 21° to 0°C.

Heat leakage

Heat entering a storage by transmission through the building material is calculated as follows:

Heat leakage in kilojoules per hour equals outside surface area in square metres multiplied by the coefficient of heat transfer ($1/R$) multiplied by the difference in temperature (degrees Celsius) from inside to outside. It is usual to use the average outside temperature for the warmest period in which the storage is to be operated and to assume an outside temperature of 5–9°C higher for the roof or ceiling than for the walls. For an uninsulated floor having perimeter insulation, the heat load of about 34.1 kJ/m^2 may be used. For an insulated floor, the $1/R$ value should be used as for the walls and ceiling, and calculations should be based on 10–13°C ground temperature. If floors are uninsulated it is desirable to have the refrigeration turned on for at least a week before heavy loading is started. Heat transmission through the floor is at first considerably greater than 34.1 kJ/m^2 and gradually becomes less, because the dry subsoil becomes an insulating medium.

Other heat sources

- Electric lights generate heat according to the rate wattage.
- Electric motors are usually rated at 2686 kJ/h.
- Forklifts produce about 36 900 kJ/h.
- Air infiltration through unprotected doors and ports may introduce a great deal of heat. Every cubic metre of air entering the storage introduces about 60 kJ at 27°C; 45 kJ at 21°C; and 32 kJ at 16°C. The ASHRAE data book (1) shows that under average conditions three complete air changes may occur in a 700-m^3 storage in 24 h and two air changes in a 1400-m^3 storage.

To determine refrigeration requirements for a storage with a floor area of 164 m^2, a wall area of 280 m^2, and a concrete floor with perimeter insulation only, see the following calculations summarized in Table 10. The capacity is about 880 m^3 and the storage holds 185 000 kg of fruit contained in 480 bulk bins. The storage is loaded at the rate of 40 bins per day, at 21°C, for 12 days. The R value of the walls is 0.95 and that of the ceiling, 1.6.

Table 10 shows the average amount of heat that must be removed every hour in order to satisfy the cooling needs. If, however, the plant is not operating continuously (for example, interruptions for defrosting), then allowances must be made to remove additional heat during the remaining period. For example, if 2 h are allowed each day for defrosting, then the total hourly load should be adjusted by a factor of 24/22, as follows: 104 200 x 24/22 h = 113 700 kJ/h. A compressor capacity of about 114 000 kJ/h is therefore needed for this storage room, with matching capacity in the evaporator coils. Compressor capacity should be based on a suction pressure corresponding to –6.5°C. Coil capacity should be based on a temperature difference

Table 10. Calculations to determine refrigeration requirements *(continued)*

Sources of heat	Amount of (kJ/h)
1. Field heat of fruit in 40 bins as calculated previously is 1 228 920 kJ/day or	51 210
2. Field heat of 40 bins is	3 940
3. Respiration heat: Maximum respiration heat of fruit that is being cooled is reached about the seventh day (Table 8) and remains a constant heat source as long as daily intake of fruit remains the same. It is $\frac{15\,400 \times 17\,800}{1000 \times 24} =$	11 420
Additional respiration heat: Fruit that has been in storage longer than 8 days and has been cooled to 0°C also produces respiration heat of about 900 kJ/t, but is not taken into account by the above calculations. This heat source should be considered in larger storages with a long loading period but could be ignored in small storages. It is included, however, to show the method of calculation. By the 12th day there would be 5 days' intake of fruit cooled to 0°C. Respiration heat would be: $\frac{5 \times 15\,400 \times 900}{1000 \times 24} =$ approximately	2 890
4. Heat transmission (walls) is 280 m^2 (area) × 1.053 kJ/m^2·°C·h × 21 (°C temperature difference) =	6 190
5. Heat transmission (floor) is 164 m^2 (area) × 34.1 kJ/h·m^2 =	5 590

Table 10. Calculations to determine refrigeration requirements (*concluded*)

Sources of heat	Amount of (kJ/h)
It is assumed that the concrete floor is laid on a well-drained base with perimeter insulation only and that the cold storage has been operating several days before loading. Under these circumstances a heat transmission rate of 34.1 kJ/h·m^2 is a reasonable figure to use (102). If the floor is insulated, the $1/R$ value of the insulation should be used instead in the calculation, and there should be about an 8°C temperature difference.	
6. Heat transmission (ceiling)	
164 m^2 (area) × 0.625 ($1/R$-value) × 30 (°C temperature difference) =	3 075
7. Electrical heat load	
Lights, 2160 kJ/h (600 W) for 8 h	
Therefore on a 24-h basis, heat generated from lights = 2160 kJ/h × 8 h =	720
Fan motors (heat given off from three fan motors, 3 hp equivalent) or 3 × 2686 kJ/h =	8 060
8. Forklift estimated time in storage 4 h about 36 900 kJ/h	
Therefore on a 24-h basis heat generated from forklift operation = 36 900 kJ × 4 h =	6 150
9. Air infiltration assumes three complete air changes in 24 h, outside air 21°C	
880 m^3 (volume of storage) × 3 h × 45 kJ/m^3 =	4 950
From data shown previously, 45 kJ heat are introduced with each cubic metre of air at 21°C	
Total amount of heat per hour	104 200

between entering and leaving air of not more than 5°C. Occasionally, it is not realized that a coil that has a 12 700 kJ/h rating at a temperature difference (TD) of 5.5°C has a 19 000 kJ/h capacity when operated at 8.5°C TD. However, to avoid freezing and desiccation of a fruit or vegetable storage, it is essential that coils be large enough to have sufficient cooling capacity when operating with a small temperature difference.

Because of their convenience and greater efficiency in moving air, ceiling-mounted unit coolers with propeller-type fans are often selected in preference to large central station blower coils with distribution ducts. For a given air delivery, propeller fans can be operated with about 900 kJ/h (1/3 hp) needed for centrifugal fans on large evaporators. With unit coolers, therefore, it becomes practical to use fans delivering up to 11 m^3/min per 12 700 kJ/h of coil capacity. A high volume of air helps to ensure rapid cooling, uniform temperature, and high humidity.

See Table 11 for temperature conversion and Table 12 for heat conversion factors.

Table 11. Temperature conversion table (*continued*)

The numbers in boldface represent temperature measured in either degrees Celsius or degrees Fahrenheit. To convert to the alternative system of measurement, locate (in the centre column) the temperature measured; then find the corresponding temperature in the right column (Fahrenheit) or the temperature in the left column (Celsius). Conversion of degrees Celsius to degrees Kelvin can be made by adding 273 to the Celsius reading.

°C		°F	°C	Temperature measured	°F	°C		°F
–40.0	–40	–40.0	–13.9	7	44.6	12.2	54	129.2
–39.4	–39	–38.2	–13.3	8	46.4	12.8	55	131.0
–38.9	–38	–36.4	–12.8	9	48.2	13.3	56	132.8
–38.3	–37	–34.6	–12.2	10	50.0	13.9	57	134.6
–37.8	–36	–32.8	–11.7	11	51.8	14.4	58	136.4
–37.2	–35	–31.0	–11.1	12	53.6	15.0	59	138.2
–36.7	–34	–29.2	–10.6	13	55.4	15.6	60	140.0
–36.1	–33	–27.4	–10.0	14	57.2	16.1	61	141.8
–35.6	–32	–25.6	–9.4	15	59.0	16.7	62	143.6
–35.0	–31	–23.8	–8.9	16	60.8	17.2	63	145.4

Table 11. Temperature conversion table (*continued*)

°C		°F	°C	Temperature measured	°F	°C		°F
-34.4	-30	-22.0	-8.3	17	62.6	17.8	64	147.2
-33.9	-29	-20.2	-7.8	18	64.4	18.3	65	149.0
-33.3	-28	-18.4	-7.2	19	66.2	18.9	66	150.8
-32.8	-27	-16.6	-6.7	20	68.0	19.4	67	152.6
-32.2	-26	-14.8	-6.1	21	69.8	20.0	68	154.4
-31.7	-25	-13.0	-5.6	22	71.6	20.6	69	156.2
-31.1	-24	-11.2	-5.0	23	73.4	21.1	70	158.0
-30.6	-23	-9.4	-4.4	24	75.2	21.7	71	159.8
-30.0	-22	-7.6	-3.9	25	77.0	22.2	72	161.6
-29.4	-21	-5.8	-3.3	26	78.8	22.8	73	163.4
-28.9	-20	-4.0	-2.8	27	80.6	23.3	74	165.2
-28.3	-19	-2.2	-2.2	28	82.4	23.9	75	167.0
-27.8	-18	-0.4	-1.7	29	84.2	24.4	76	168.8
-27.2	-17	1.4	-1.1	30	86.0	25.0	77	170.6
-26.7	-16	3.2	-0.6	31	87.8	25.6	78	172.4
-26.1	-15	5.0	0.0	32	89.6	26.1	79	174.2
-25.6	-14	6.8	0.6	33	91.4	26.7	80	176.0
-25.0	-13	8.6	1.1	34	93.2	27.2	81	177.8
-24.4	-12	10.4	1.7	35	95.0	27.8	82	179.6
-23.9	-11	12.2	2.2	36	96.8	28.3	83	181.4

Table 11. **Temperature conversion table** (*concluded*)

°C		°F	°C	Temperature measured	°F	°C		°F
–23.3	–10	14.0	2.8	37	98.6	28.9	84	183.2
–22.8	–9	15.8	3.3	38	100.4	29.4	85	185.0
–22.2	–8	17.6	3.9	39	102.2	30.0	86	186.8
–21.7	–7	19.4	4.4	40	104.0	30.6	87	188.6
–21.1	–6	21.1	5.0	41	105.8	31.1	88	190.4
–20.6	–5	23.0	5.6	42	107.6	31.7	89	192.2
–20.0	–4	24.8	6.1	43	109.4	32.2	90	194.0
–19.4	–3	26.6	6.7	44	111.2	32.8	91	195.8
–18.9	–2	28.4	7.2	45	113.0	33.3	92	197.6
–18.3	–1	30.2	7.8	46	114.8	33.9	93	199.4
–17.8	0	32.0	8.3	47	116.6	34.4	94	201.2
–17.2	1	33.8	8.9	48	118.4	35.0	95	203.0
–16.7	2	35.6	9.4	49	120.2	35.6	96	204.8
–16.1	3	37.4	10.0	50	122.0	36.1	97	206.6
–15.6	4	39.2	10.6	51	123.8	36.7	98	208.4
–15.0	5	41.0	11.1	52	125.6	37.2	99	210.2
–14.4	6	42.8	11.7	53	127.4	37.8	100	212.0

Table 12. Heat conversion factors

Multiply	by	to obtain
Btu*	1.055	kJ
Btu/ft^3	37.3	kJ/m^3
Btu/gal	0.279	kJ/L
Btu·in./h·ft^2·°F (thermal conductivity, *K*)†	0.144	W/(m·°K) W/(m·°C)
Btu/h	0.293	W
Btu/ft^2	11.4	kJ/m^2
Btu/(h·ft^2)	3.15	W/m^2
Btu/(h·ft^2·°F) (overall heat transfer coefficient, *U*) (thermal conductance, *C*)	5.68	W/(m^2·K) W/(m^2·°C)
Btu/lb	2.33	kJ/kg
Btu/(lb·°F) (specific heat, *C*)	4.19	kJ/(kg·°K) kJ/(kg·°C)
calorie	4.19	J
horsepower (550 ft·lbf/s)	0.746	kW
ton, refrigeration (12 000 Btu/h)	3.52	kW
to obtain	by	Divide ‡

*British thermal unit (Btu). Quantity of heat required to raise the temperature of 1 lb of water 1°F (3.41 Btu/h = 1 W = 3.6 kJ/h).

†Thermal conductivity (*K*). Indicates the rate of heat transfer through a material and is equivalent to the number of British thermal units moving through 1 ft^2 of material 1 in. thick in 1 h for each degree Fahrenheit.

‡To obtain Imperial measurements, divide figure in the last column by figure in the centre column.

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CONVERSION FACTORS FOR METRIC SYSTEM

Imperial units	Approximate conversion factor	Results in
Linear		
inch	× 25	millimetre (mm)
foot	× 30	centimetre (cm)
yard	× 0.9	metre (m)
mile	× 1.6	kilometre (km)
Area		
square inch	× 6.5	square centimetre (cm^2)
square foot	× 0.09	square metre (mm^2)
acre	× 0.40	hectare (ha)
Volume		
cubic inch	× 16	cubic centimetre (cm^3)
cubic foot	× 28	cubic decimetre (dm^3)
cubic yard	× 0.8	cubic metre (m^3)
fluid ounce	× 28	millilitre (mL)
pint	× 0.57	litre (L)
quart	× 1.1	litre (L)
gallon	× 4.5	litre (L)
bushel	× 0.36	hectolitre (hL)
bushel	× 0.0352	cubic metre (m^3)
Weight		
ounce	× 28	gram (g)
pound	× 0.45	kilogram (kg)
short ton (2000 lb)	× 0.9	tonne (t)
Temperature		
degrees Fahrenheit	(°F-32) × 0.56 or (°F-32) × 5/9	degrees Celsius (°C)
Pressure		
pounds per square inch	× 6.9	kilopascal (kPa)
Power		
horsepower	× 2690	kilojoules (kJ/h)
Speed		
feet per second	× 0.30	metres per second (m/s)
miles per hour	× 1.6	kilometres per hour (km/h)